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BRITISH MUSEUM (NATURAL HISTORY)

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THE  
JOHN MURRAY EXPEDITION  
1933-34

SCIENTIFIC REPORTS

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VOLUME II

METEOROLOGICAL, CHEMICAL  
AND PHYSICAL INVESTIGATIONS



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BY

JAMES PATON, M.A., B.Sc.

WITH NINE TEXT-FIGURES



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1936

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[Issued 24th October 1936]







# REPORT ON THE METEOROLOGICAL OBSERVATIONS

BY

JAMES PATON, M.A., B.Sc.

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WITH NINE TEXT-FIGURES.

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THE observations, on which the following report is based, fall into two series :

I. Throughout the course of the John Murray Expedition meteorological observations were taken at four-hourly intervals on the "Mabahiss"; Dr. H. Faouzi, Director of Fishery Research, Egyptian Coastguard and Fishery Service, was in charge of these observations throughout the whole period and from 8 a.m. to 8 p.m. inclusive they were taken by him personally, while at midnight and at 4 a.m. they were taken by the officer of the watch, who was on duty.

The observations taken were as follows :

- (a) Height of the barometer.
- (b) Air temperature, dry and wet bulb.
- (c) Sea surface temperature.
- (d) Wind direction, observed.  
Wind force in miles per hour.
- (e) Ship's course.
- (f) Ship's speed.

The observations on the wet-bulb thermometer were not taken at midnight or at 4 a.m., and items (e) and (f) were obtained from the ship's log.

The "Mabahiss" was supplied on loan by the Meteorological Department of the Air Ministry, London, with an Assmann psychrometer and a cup-anemometer with electrical recording apparatus. The anemometer was fitted to an upright above the awning on the upper navigating bridge and the recorder was situated in the wheel-house. The position at which observations were taken by means of the Assmann psychrometer varied according to circumstances. Every effort was made to select a site where the temperature readings would not be affected by radiation from bulkheads or heating from the

engine-room, while at the same time avoiding, so far as was possible on such a small vessel, any possibility of spin-drift settling on the dry-bulb thermometer. Observations of the sea-surface temperature were taken by collecting the surface-water sample in a leather or wooden bucket and placing the thermometer in the bucket as soon as the sample reached the deck.

II. Thanks to the kind offices of the Meteorological Department of the Air Ministry, London, it was arranged that observations on the sea-surface temperature, and the wind direction (true) and wind force, should be made by a number of ships of the British Merchant Service throughout the whole year from September, 1933, to September, 1934, along three routes, namely :

(i) Between Aden and Karachi.

(ii) Between Aden and Bombay.

(iii) Between Aden and Colombo, or, in the case of vessels not actually calling at this latter point, between Aden and long.  $80^{\circ}$  E.

The vessels which volunteered for this work, were supplied with a standard pattern thermometer, and the observations were taken at 4-hourly intervals (apparent time) by the officer of the watch.

In addition to the above three series of observations, a fourth series was very kindly carried out by arrangement with the British India Steam Navigation Co. Ltd. between Bombay and Mombasa.

### §1. WIND.

The observations were made in the Indian Ocean from the beginning of November until the end of April, and the normal conditions in the NE. monsoon, the steady moderate breeze, were experienced. There is no indication of the 12-hourly variation in velocity observed in the Atlantic by the "Challenger" Expedition.

### §2. HUMIDITY.

The mean humidity over the open sea increased from about 75% in the North Arabian Sea to over 80% in the South, and the normal slow increase towards the end of the monsoon period was observed. Single observations of humidity greater than 90% were infrequent.

### §3. SEA SURFACE TEMPERATURES.

In addition to the sea surface temperature observations of the "Mabahiss", similar observations at the same hours were taken by ships of the British Merchant Navy in connection with water sampling in the Arabian Sea. In Vol. V, 1928, of the 'Marine Observer', are given monthly mean sea temperatures for areas of  $2^{\circ}$  of longitude by  $2^{\circ}$  of latitude computed from observations taken between 1855 and 1917. These have been used for the purpose of comparison, to show any marked deviations from the normal sea surface temperature distribution which may have occurred during the period of the Expedition. It will be obvious that local temperature variations will not be shown in such comparisons over areas as large as  $2^{\circ}$  squares.



The table given below is for the voyage of the "Mabahiss" :

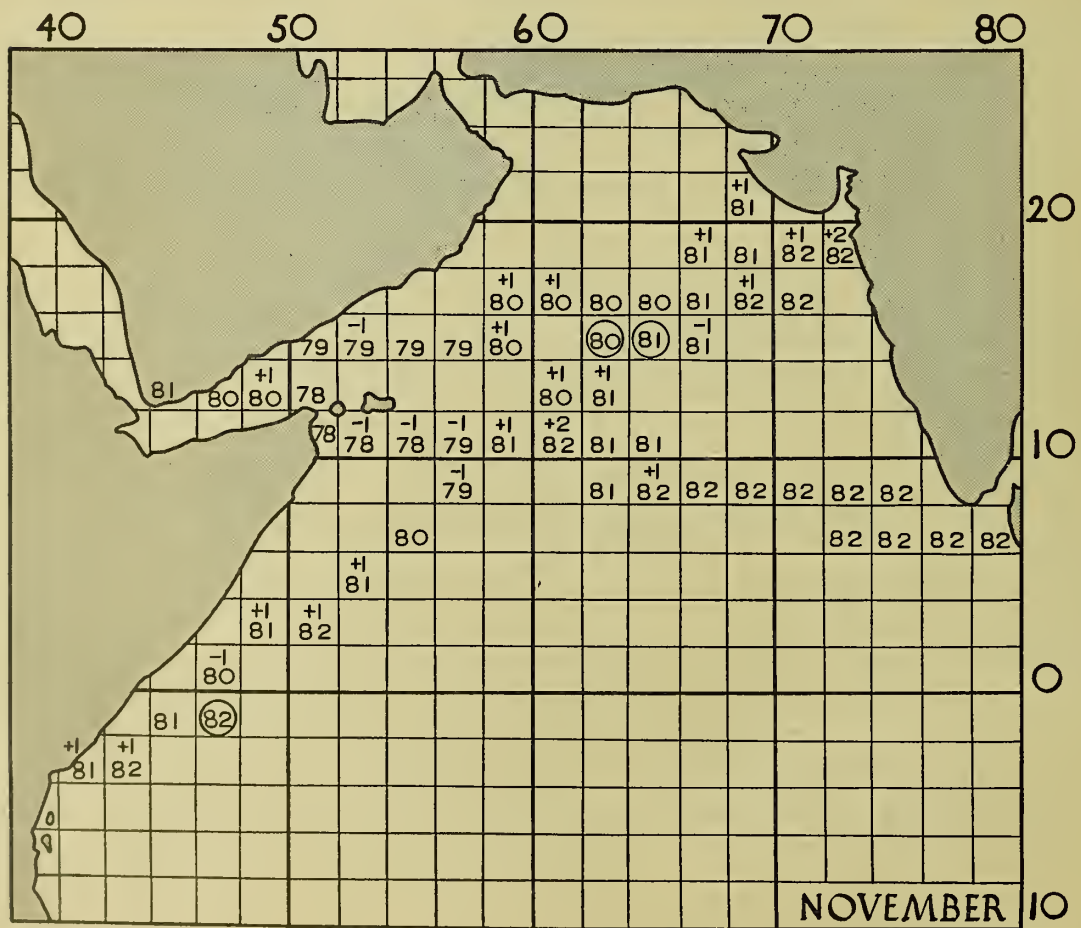
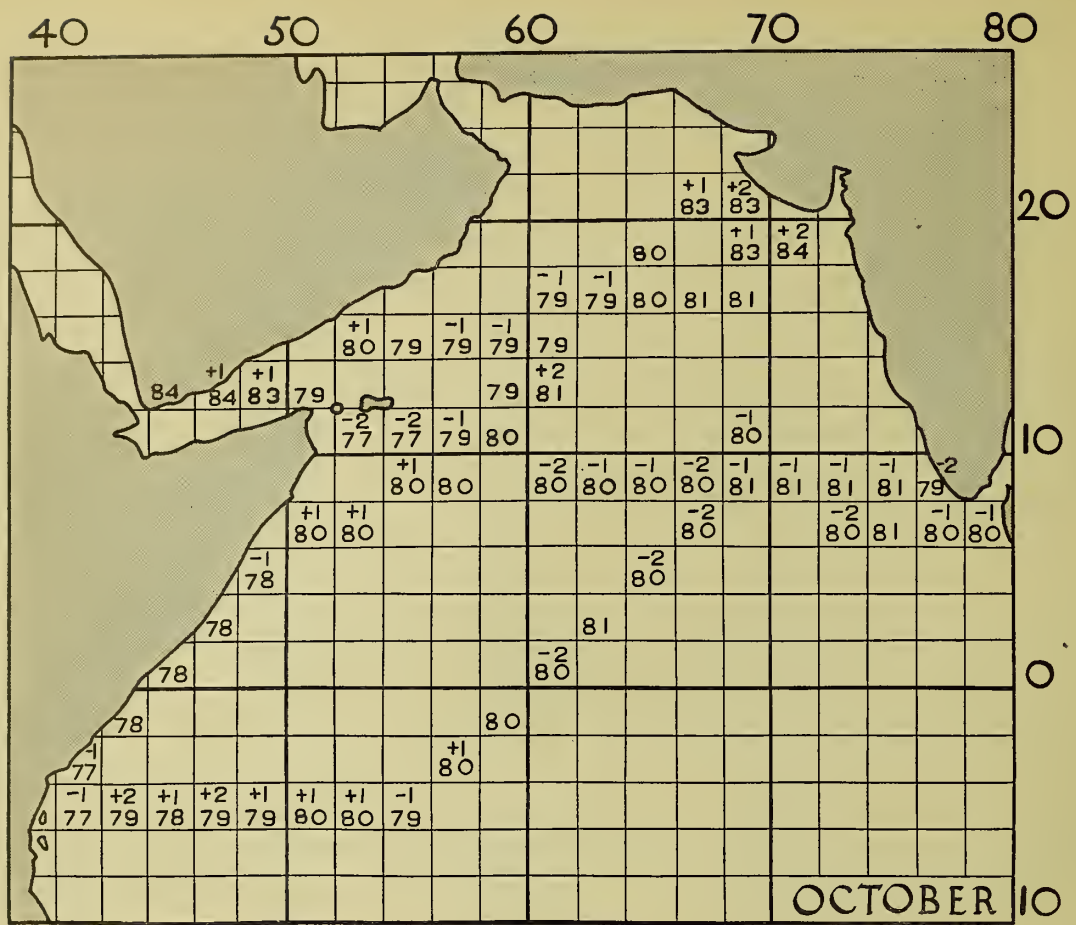
Cruise.	Dates (1933).	Positions (Stations).	Mean temperatures (° F.).	Approximate normal temperature (' Marine Observer' (° F.).
I.	13.ix-18.ix	5-11	88.4	89.0
	19.ix-21.ix	12-18	85.5	85.0
II.	5.x-8.x	22	73.6	77.0
	9.x-12.x	23-29	82.4	79.0
	14.x-15.x	32-33	81.5	80.0
	16.x	34-35	84.8	83.0
III.	24.x-2.xi	38-53	79.5	80.0
	4.xi-9.xi	55-61	80.6	80.0
IV.	18.xi-21.xi	62-65	78.8	79.0
	24.xi-28.xi	68-75	78.8	78.0
	29.xi-3.xii	76-82	79.2	78.0
	4.xii-7.xii	83-90	80.6	78.6*
V.	14.xii-30.xii	91-102	79.5	79.0*
(1934.)				
VI.	11.i-24.i	103-126	79.7	81.0
VII.	31.i-5.ii	127-129	81.5	82.4*
	9.ii-21.ii	131-135	81.7	82.0*
VIII.	18.iii-25.iii	135-139	83.5	83.0
	10.iv-12.iv	162-165	85.6	84.5
IX.	20.iv-30.iv	166-173	84.0	84.0*
	1.v-4.v	175-184	83.1	82.4
	5.v-7.v	185-194	83.8	83.5
X.	14.v-15.v	199-202	84.2	85.0
	16.v-17.v	203-209	83.5	84.4

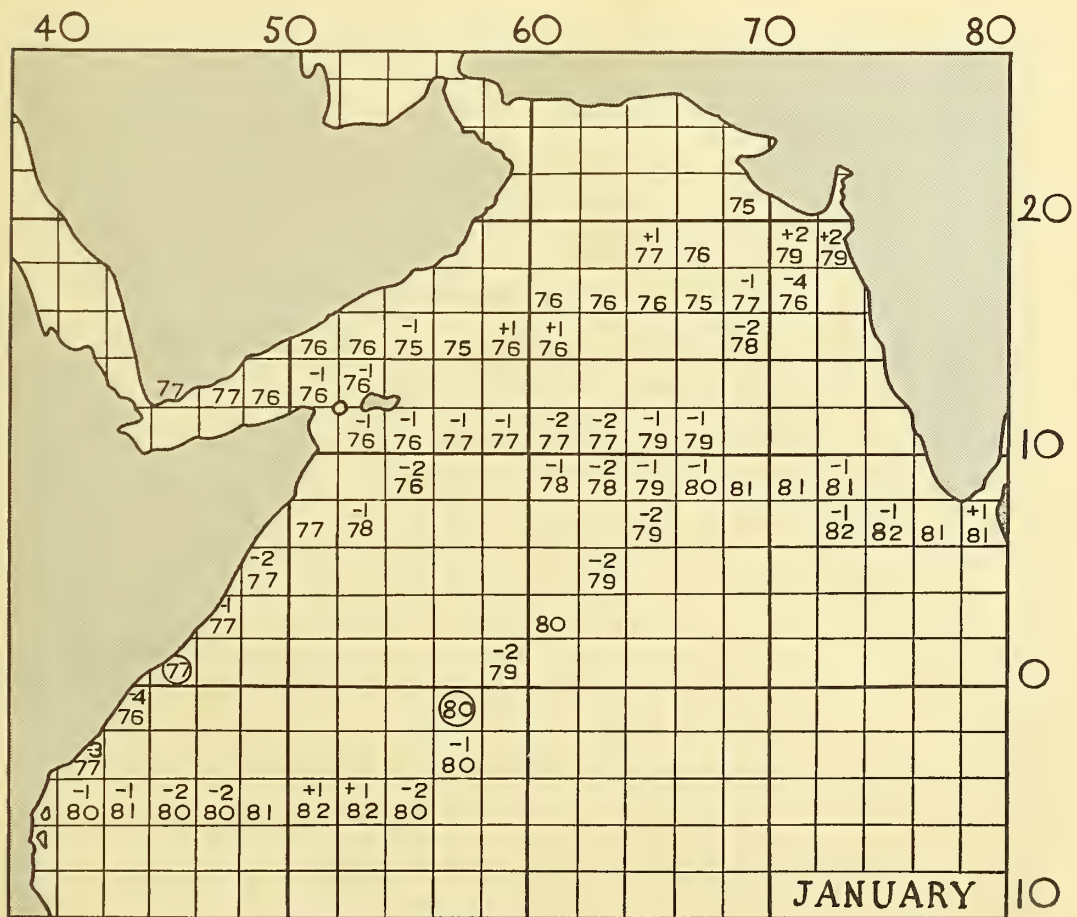
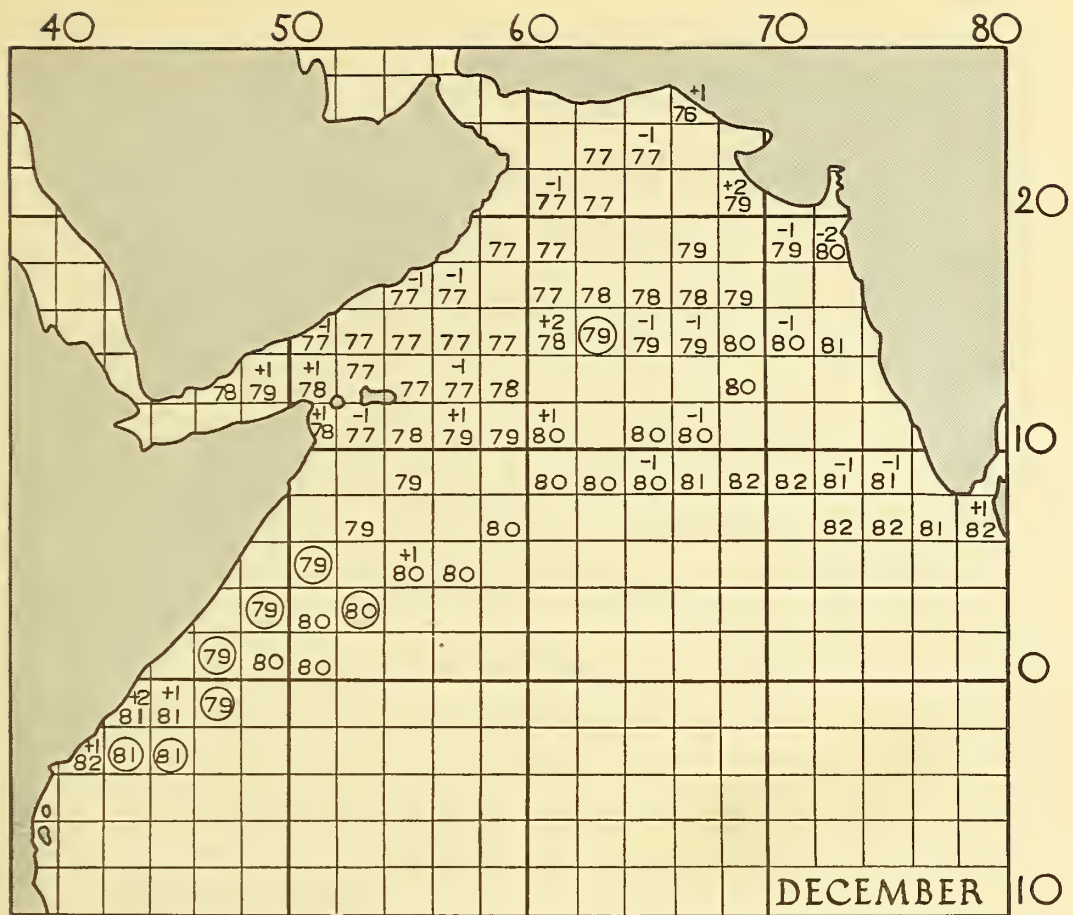
\* Open seas.

Except for local variations in the currents off Cape Guardafui (Stations 22-29), temperatures over the sea in coastal areas show no great deviations from normal. Approximately normal temperatures, too, were encountered by the "Mabahiss" in the open sea in all areas except at the head of the Arabian Sea (Stations 83-90), where the waters appear to have been appreciably warmer than is usual at this time of year.

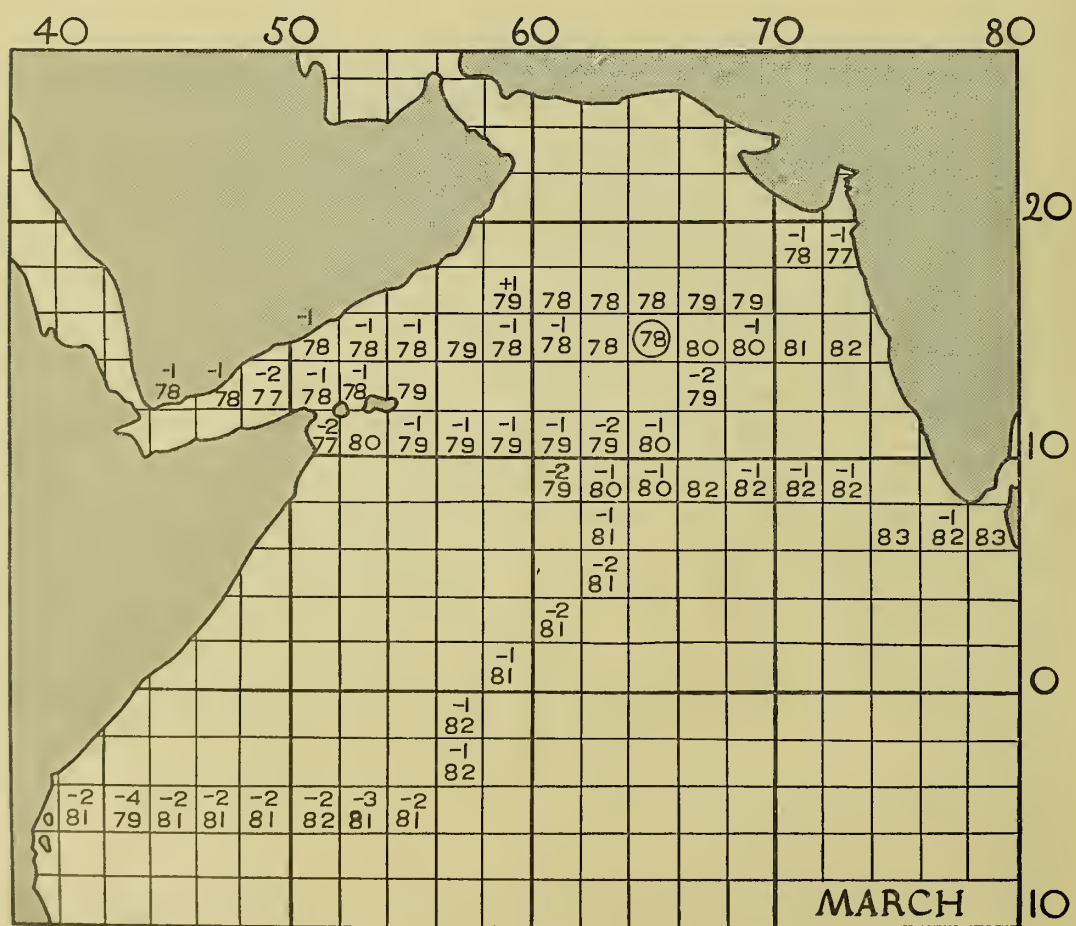
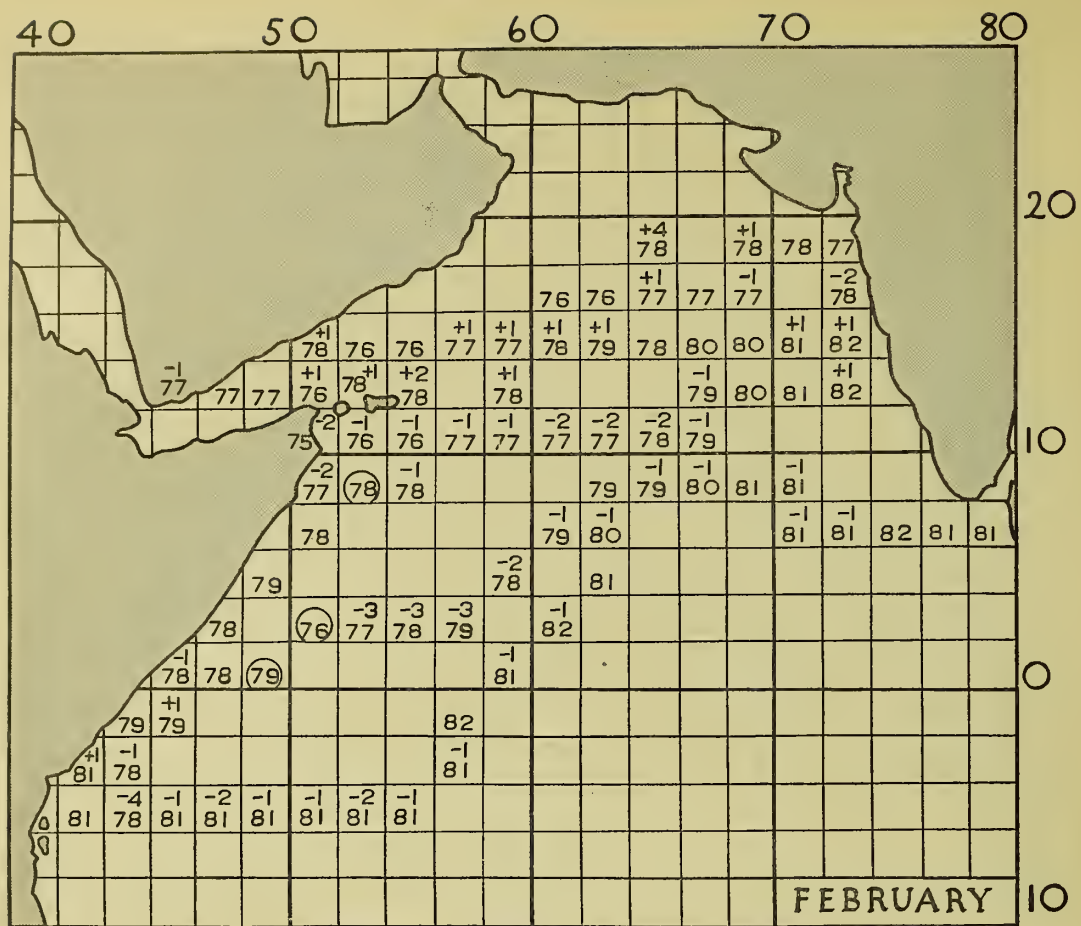
The charts of mean sea temperature for the months October, 1933-May, 1934 have been prepared from data supplied by the Merchant Navy. All deviations from normal temperature as given in the 'Marine Observer' are inserted above the actual mean temperature for the month for each square. When no data for comparison are available the figure has been ringed.

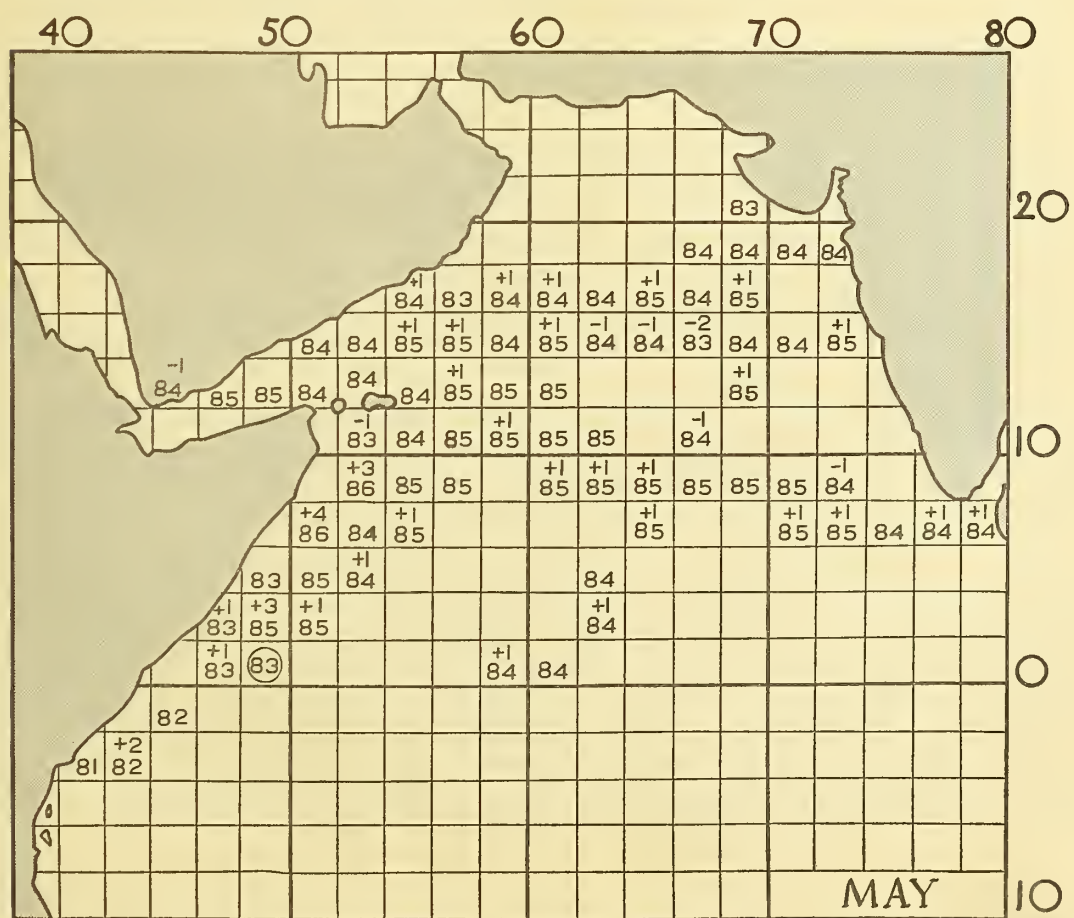
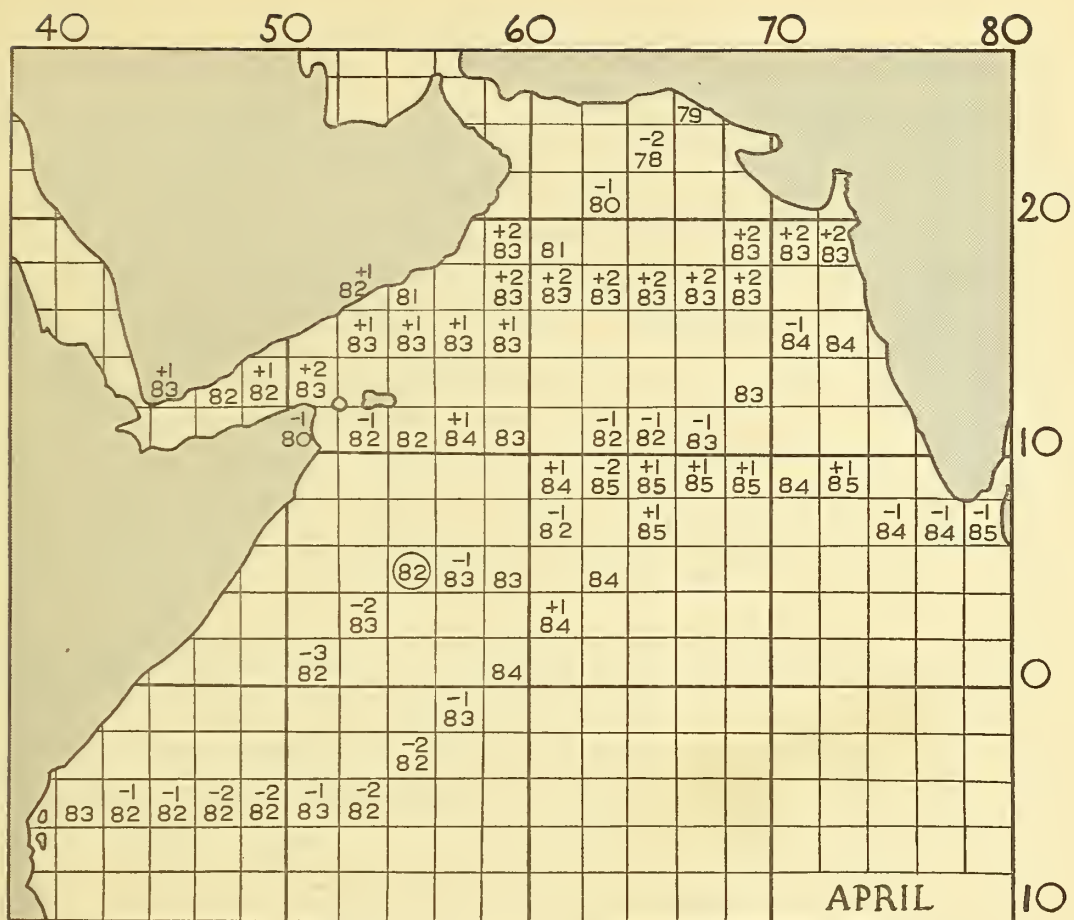
Deviations of 1° F. in these charts are not very significant, as each mean given is the average of from 3 to at the most 12 sets of observations. The values for areas in the region of 10° N. latitude, the most frequented part of the Arabian Sea, are the most reliable. In October, 1933, and January, February and March, 1934, sea temperatures in this region tended to be slightly below normal. The chart for December, when many observations were available, shows clearly the NE.-SW. direction of the isotherms following the set of











the current in the western half of the Arabian Sea. The large difference in temperature normally obtaining in February between the colder waters at the head of the Arabian Sea and those at about  $10^{\circ}$  N. latitude, to which the reversal of current while the NE. monsoon is still blowing is attributed (Barlow, 1935), was apparently much reduced in 1934.

It is important to note here some results of Harvey (1925) which have a direct bearing on the measurement of sea surface temperatures. He shows that in quiet weather the upper inch or two of water may be so heated by solar radiation that a sharp surface of temperature discontinuity develops under it. It appears that this temperature distribution, once produced, may then persist through several days of rough weather, so that temperature observations made by the bucket method may give values considerably lower than the actual surface water temperature. This effect would be especially well marked in the Indian Ocean during the period of these observations (November–March or April), when there is little cloud and generally never more than a light to moderate breeze.

#### §4. THE DIURNAL VARIATION OF TEMPERATURE OF THE OPEN WATERS OF THE ARABIAN SEA.

The deviations from the mean day sea surface temperature have been determined for each hour of observation for 52 days of the five periods between December, 1933 and April, 1934, when the ship was in the open sea.

The averages of these are as follows :

	Hour.					
	4.	8.	12.	16.	20.	24.
Deviation from mean day temperature ( $^{\circ}$ F.) .	−0.8	−0.1	+0.5	+0.6	+0.2	−0.7

An interesting point emerges from these figures. Following a very rapid fall in temperature between 20 hours and midnight, there is only a slight cooling of the sea surface between midnight and 4 a.m. On examination, it was found that the observations of the “Challenger” Expedition (Buchan, 1889) in the open waters of the North Atlantic (mean latitude  $30^{\circ}$  N. and longitude  $42^{\circ}$  S.) between March and August show a similar effect, with the corresponding hourly deviations of −0.3, −0.1, +0.2, +0.5, 0.0, −0.3.

It appears, then, that radiation losses from the water surface are small, and that the sudden fall in sea surface temperature after sunset is due mainly to losses from evaporation, assisted possibly by the mixing of upwelling colder water with the surface layer heated during the day.\* An examination of the diurnal variation of the air temperature over the open sea (see §5) shows that, in contrast to the sea surface variation, the air temperature falls quite slowly from 20 hours to midnight and then very rapidly until 4 a.m. Thus evaporation from the sea surface will be but slightly reduced from sunset to midnight, but will be very effectively checked between midnight and 4 a.m. It will be observed also that cooling between 20 hours and midnight is much slower in the Atlantic than in

\* The question of the relative efficiency of radiation and evaporation in cooling the sea surface has been examined by Harvey (1925), who finds that surface heat losses are influenced to a much greater extent by evaporation than by radiation.



the Arabian Sea, where all the observations were made during the period of the comparatively dry and very steady NE. monsoon—conditions producing great evaporation.

The mean temperatures and the mean daily range for the five cruises in question are :

Position.	Date. (1933).	Mean sea temperature (° F.).	Mean daily range (° F.).
81-86	2.xii-6.xii	80.0	1.4
91-102	14.xii-30.xii	79.5	1.4
(1934.)			
127-129	31.i-5.ii	81.5	1.3
130-135	9.ii-21.ii	81.7	1.6
Colombo-173	20.iv-30.iv	84.0	2.3

For the whole period of the observations the mean daily range is 1.6° F.

The marked difference between the diurnal ranges in December-February and in April led to the examination of the daily variation for these two periods separately.

The respective values are :

December-February	. -0.7	. -0.1	. +0.5	. +0.5	. +0.2	. -0.6
April	. -1.0	. -0.1	. +0.6	. +1.0	. +0.3	. -0.8

The much greater range in April results almost entirely from the increased intensity of solar radiation. There is an increase in average humidity and decrease in wind speed, but both are so slight that the resultant decrease in evaporation is quite negligible.

#### §5. THE DIURNAL VARIATION OF AIR TEMPERATURE OVER THE OPEN SEA.

The averages of the deviations from the mean day air temperature at each hour of observation have been calculated for 48 days when the ship was in the open sea, during periods between December and April. They are :

	Hour.					
	4.	8.	12.	16.	20.	24.
Deviation from mean (°F.)	-0.7	-0.2	+0.3	+0.7	0.0	-0.3

These deviations are considerably less than those given by Dallas (1894) for the same area and time of year. The corresponding values of the deviations obtained from Dallas's tables are -1.3, -0.1, +1.4, +1.3, -0.4, -0.9, while those of Buchan for 126 days in the open waters of the North Atlantic between March and August are -1.4, -0.2, +1.4, +1.6, -0.3, -1.0.

The disturbing effect of the ship on the surrounding air due to heating by solar radiation by day and cooling at night renders the observation of the true air temperature over the sea extremely difficult, and it seems probable that the greater deviations shown by Dallas, while partly the result of smoothing out in the process of averaging the present observations for different areas, is mainly due to differences in the mounting and screening of the thermometers. This radiation effect is particularly noticeable when the ship is stationary. For example, on February 3rd, 1934, when the ship was drifting in the open

sea (Station 128) and the wind 7 miles per hour with no appreciable change in direction, the air temperature rose by as much as  $3.6^{\circ}$  F. between 8 a.m. and noon. Again, during the night of April 23rd–24th, when the ship was carrying out hydrographic observations at Station 166 in a light wind, the temperature fell by  $3.3^{\circ}$  F. between midnight and 4 a.m., while, when the ship got under way again, the thermometer showed a rise in temperature of  $3.7^{\circ}$  F. by 8 a.m. Days showing such radiation effects to a marked degree were omitted when estimating the values given above.

These effects may persist, though in a much less degree, when the ship is in motion, so that it appears that the true diurnal variation of the air temperature over the open sea is normally very small—certainly less than would appear from observations aboard ship.

On the other hand, spindrift blown into the screen on to the thermometer bulb will cause the readings to be too low, but the conditions actually experienced in the open sea, the comparatively dry and seldom more than moderate breeze, would not be such as to make this effect appreciable.

Of course, since observations were made at 4-hourly intervals only, the actual thermometric range will be somewhat greater than the observed one. The "Challenger" 2-hourly observations showed that the minimum temperature occurred between 4 and 6 a.m. and the maximum at about 2 p.m., and Sewell (1927) observes that the average temperature at 4 p.m. is roughly  $2^{\circ}$  F. lower than at 2 p.m. This correction is applied by him to determine the average daily range of temperature in the open waters of the Indian Seas. This is found to be  $2.3^{\circ}$  F. The present observations for the period December to April show an average daily range of  $2.0^{\circ}$  F. for all days when the ship was in the open sea—that is, an actual range of  $2.2^{\circ}$  F., assuming Sewell's correction. Buchan's "Challenger" observations are given for comparison :

Place.	Range ( $^{\circ}$ F.).
South Atlantic . . . . .	2.5
North Pacific . . . . .	3.1
South Pacific . . . . .	4.0
Atlantic (Equator) . . . . .	2.6
Pacific (Equator). . . . .	2.1

The smaller diurnal range in air temperature in equatorial regions is explained by Buchan as being due to the greater average cloudiness in these areas.

The mean daily air temperature and daily range for each of the five cruises in the open sea is as follows :

Position (Stations).	Date (1933).	Mean temperature ( $^{\circ}$ F.).	Mean daily range ( $^{\circ}$ F.).
81–90 .	2.xii–7.xii .	78 .	1.5
91–102 .	14.xii–30.xii .	79 .	1.6
127–129 .	31.i–5.ii .	81 .	2.0
130–135 .	9.ii–21.ii .	81 .	2.0
Colombo–173 .	20.iv–30.iv .	84 .	2.0



*The Diurnal Variation of Air Temperature in Coastal Regions.*

In contrast to the low values of daily range of air temperature over the open sea, the range in coastal areas may be very great. The average of the observed daily range on the cruise from Aden to Karachi along the Arabian coast was  $5.4^{\circ}$  F. The greatest daily range then observed was  $9.8^{\circ}$  F. on November 4th—apparently a cloudless day with a light wind; while the lowest was  $3.0^{\circ}$  F. on October 30th, when there was much cloud present and a moderate breeze blowing mainly off the sea.

In the Gulf of Aden on October 3rd, a range in air temperature of as much as  $13.5^{\circ}$  F. was observed.

## §6. THE DIFFERENCE IN TEMPERATURE BETWEEN THE SURFACE OF THE SEA AND THE OVERLYING AIR.

This is of decided importance from the point of view of local weather conditions, for a sea temperature below that of the overlying air results generally in the development of fog, while the reverse produces convection in the atmosphere.

It has to be borne in mind that the air temperature is determined on the deck of the ship, possibly some 15 to 20 feet above the sea level, by using a thermometer, effective screening of which is almost impossible; while sea temperatures obtained by the bucket method may give readings much below the actual surface temperature.

Considering the same 48 days as were used to estimate the diurnal variation of air temperature over the open sea (that is, omitting those showing marked radiation effects), an attempt was made to analyse the diurnal variation of the difference sea-air temperature. Though observations were for five cruises during periods from December to April, so that actual temperature differences varied for each,\* a similar daily variation was evident throughout. The average for the five cruises is:

	Time.					
	4.	8.	12.	16.	20.	24.
Difference sea-air temperature ( $^{\circ}$ F.)	+0.7	+0.7	+0.9	+0.5	+0.9	+0.5

The meaning of this diurnal variation is made clear by considering together the diurnal variation of sea and air temperature which are plotted on one graph.

Although readings at 4-hourly intervals necessarily give only a rough indication of the actual variation, they are sufficient to explain the above diurnal variation of the difference sea-air temperature.

\* The mean temperature differences for the different areas and times are given here:

Dates.	Stations.	Average difference sea-air. ( $^{\circ}$ F.).
2. xii-7. xii	82-90	1.6
14. xii-30. xii	92-102	0.5
31. i-5. ii	127-129	0.9
9. ii-21. ii	130-135	0.5
20. iv-30. iv	166-173	0.5

The large average difference at the head of the Arabian Sea is due to the comparatively low temperature of the air brought from the north by the monsoon.

It will be seen from the graph that—

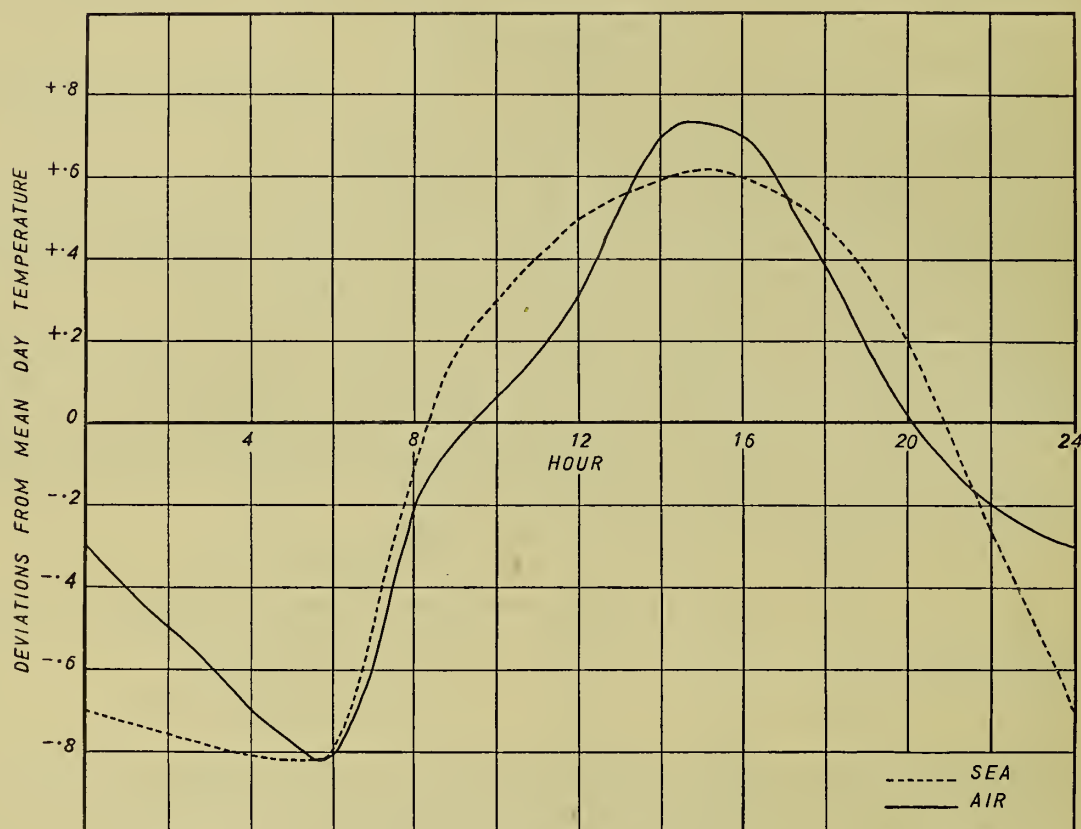
(a) From about 6 to 12 hours the sea by insolation increases in temperature more rapidly than the overlying air.

(b) From 12 to 16 hours the air temperature rises more rapidly than the sea surface temperature.

(c) From 16 to 20 hours the air temperature falls faster than the sea temperature.

(d) From 20 to 24 hours the sea surface cools more quickly than the air, and—

(e) From midnight to 4 hours the air temperature falls more rapidly than the sea.



Effects (b) and (c) must be exaggerated by and may even be due to errors introduced through the impossibility of effectively screening the air thermometer, which will certainly read higher than the actual air temperature round about noon and 14 hours. That is, the air thermometer will show a more rapid increase in temperature after about noon than is actually the case and, of course, a more rapid decrease when solar radiation falls off. Similarly, effect (e) must, at least in part, result from local radiation cooling, which causes the air thermometer to give readings below the true air temperature. Each of these effects will be particularly well marked when the sky is clear and the wind light. Effect (d) is due to the very rapid drop in sea surface temperature after sunset which we have already examined.

It would seem, then, that under the conditions obtaining between December and April in the open waters of the Arabian Sea, the temperature of the lower layers of air rises and falls at approximately the same rate as the sea surface temperature, but the matter can only be thoroughly examined by a consideration of the lapse rate of temperature above the sea.

Professor Brunt has called my attention to papers on vertical gradients of temperature in the lower layers of the atmosphere over the Baltic and Mediterranean Seas by Wüst (1920) and Johnson (1927) respectively.

Wüst arranged for observations of temperature by Assmann psychrometers to be made at different heights above the sea, aboard a schooner (at heights of 9, 6, 4 and 2 metres), and on a dinghy situated about 150 metres from the schooner on the weather side (at heights of 0.2, 0.5, 1.2 and 2.0 metres). The local radiation effects outlined in paragraph 5 showed themselves clearly in the simultaneous readings at 2 metres on the schooner and dinghy. On the average, the temperature recorded at 2 metres on the schooner was  $0.41^{\circ}\text{F}$ . higher than on the dinghy, while in individual cases with bright sunshine, the difference was as high as  $1.4^{\circ}\text{F}$ . Examination of Wüst's temperature observations shows that (1) in bright weather the lapse rate in temperature up to the highest point of observation (9 metres) is very much in excess of the dry adiabatic lapse rate, and (2) in cloudy weather extremely high temperature gradients occur in the lowest metre, but above 6 metres the lapse rate decreases to approximately adiabatic. The air temperatures observed in cloudy conditions, when the radiation effect of the ship is much reduced, will approximate more closely to the true conditions, and the very large temperature gradient then observed near the surface emphasizes the influence of the sea in heating the air. Thus, in bright weather, the radiation from this small schooner (36 metres long, deck at  $1\frac{1}{2}$  metres) affects the thermometer readings even at 9 metres and smooths out the super adiabatic lapse rate, so that it appears to persist slightly reduced up to a considerable height above the sea.

Johnson made careful observations of temperature gradient over the Mediterranean by platinum resistance thermometers carried at the mast-head (22 metres) and over the bows (5 metres). Observations were also made at 2 metres by lowering the forward element. His results are similar to those of Wüst, namely, a very high lapse rate near the surface falling slowly until at about 10 metres it becomes adiabatic.

It may be concluded that above a height of a few metres the lapse rate above the sea normally approximates to the dry adiabatic lapse rate.

Johnson finds that during the day the lapse rate between 5 and 22 metres is approximately the dry adiabatic, but that during the night it increases considerably. Assuming *no* diurnal variation of the sea temperature, he explains the increased lapse rate at night as due to the diurnal variation of air temperature (found to be  $1.9^{\circ}\text{F}$ .). The present observations in the Arabian Sea show that the sea temperature actually has a diurnal variation very similar to that of the overlying air, and the fact that the air temperature rises and falls at approximately the same rate as, and almost simultaneously with, the sea surface temperature appears to indicate that the diurnal variation of air temperature *is a result of* the diurnal variation of sea temperature.

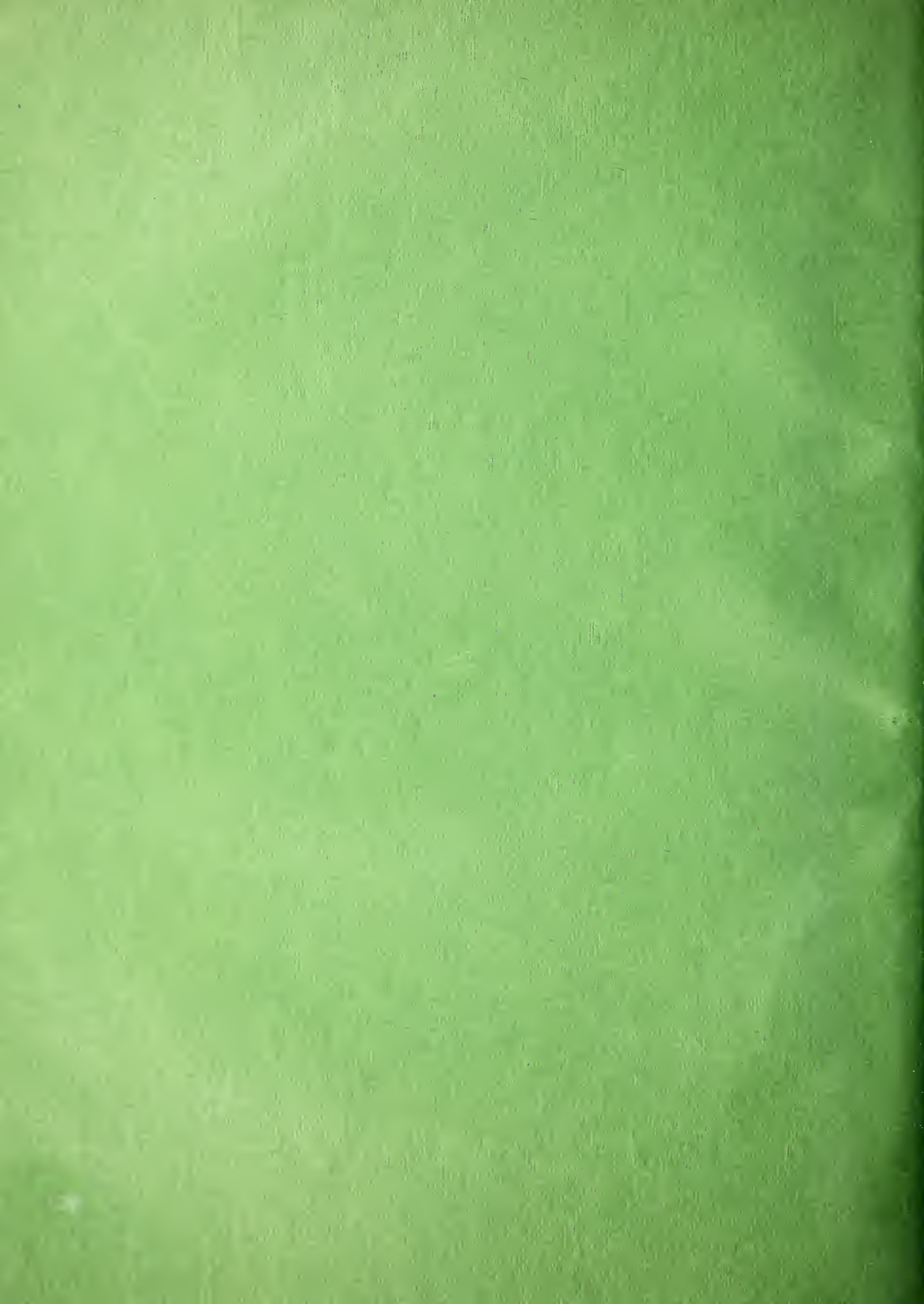


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THE  
JOHN MURRAY EXPEDITION  
1933-34

SCIENTIFIC REPORTS

VOLUME II. No. 2

CHEMICAL AND PHYSICAL  
INVESTIGATIONS

INTRODUCTION

BY

E. F. THOMPSON, M.Sc.(N.Z.), Ph.D.(CANTAB.) AND  
H. CARY GILSON, M.A.

WITH SIXTEEN TEXT-FIGURES AND ONE CHART



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# CHEMICAL AND PHYSICAL INVESTIGATIONS

## INTRODUCTION

BY

E. F. THOMPSON, M.Sc.(N.Z.), PH.D.(CANTAB.) AND  
H. CARY GILSON, M.A.

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WITH 16 TEXT-FIGURES AND ONE CHART.

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THE results recorded in the present volume are those of the hydrographical and chemical investigations carried out by the John Murray Expedition of September, 1933, to May, 1934. A general account of the ship and apparatus and a brief narrative of the cruise are given in the previous volume,\* where a map showing the course sailed and the positions of stations is attached. The present introduction is confined to the special methods and conditions affecting the hydrographic results. Two sections of the chemical work are dealt with separately by other authors. Mr. Gilson deals with the nitrogen cycle in the area, with particular reference to its interrelations with plankton production; while Mr. Mohamed considers the values of hydrogen-ion concentration. The details of the methods employed by these two workers will be given in their particular sections.

The aims of the hydrographic work were twofold. First, the characterization of the different water masses, their circulation, and the effects of the seasonal winds on this circulation; secondly, the correlation between these facts and the biological conditions.

## APPARATUS AND EQUIPMENT.

### (a) THE HYDROGRAPHIC WINCH.

This was supplied by Messrs. Elliott & Garrood, of Beccles, and installed when the ship was built. Its engine and general arrangement were perfectly satisfactory, but its main drum, intended to take 3000 fathoms of wire, proved too weak for work at depths greater than 2000 fathoms. Being too deep and too narrow in shape, its flanges were not

\* Vol. I, No. 1. 'Introduction and List of Stations', by Lt.-Col. R. B. Seymour Sewell, C.I.E., Sc.D., F.R.S., I.M.S.(ret.).

stiff enough to take the very great lateral pressure when full of wire. One flange cracked at Station 22. This was repaired in Karachi, and lasted fairly well, until it cracked again at Station 127. For many stations we were compelled to use the small drum of the big trawling winch. This worked well, if rather slowly, and had the advantage that the lead for the wire was more convenient.

(b) THE WIRE.

The wire used was 4 mm. in diameter and made of hardened spring steel. In all we had some 8000 fathoms, most of which consisted of six strands, each made up of seven wires. One length was of an extra flexible type consisting of six strands each of nineteen much finer wires, and was much easier to splice and pleasanter to work with, and seemed to wear equally well. The wire was greased both when running out and when being hauled in, on the earlier cruises with a heavy motor-gear oil, and on the latter ones with a castor oil and tallow mixture used for the trawl warp. What rusting occurred was almost entirely superficial, and no trouble was experienced from this cause.

(c) BLOCKS.

We had at first no special blocks for the hydrographic wire and used ordinary small iron blocks. These caused considerable trouble, the wire cutting rapidly into the cast-iron sheaves. Thus it twice happened that a sheave collapsed while in use. Later a special block was made for us by Messrs. R. W. Munro & Co. with a heavy bronze sheave, some 8 inches in diameter, mounted on ball bearings, fitted with "Tecalemit" greasing nipples. This block worked perfectly even at the highest speeds, and we had no further trouble from this cause.

The wire was led straight forward from the winch, through this special block suitably placed, then through a spring-loaded "accumulator" mounted on a davit, and finally out over the measuring sheave. This last was simply a large ball-bearing block containing a sheave 1 metre in circumference coupled to a revolution counter. The accumulator served to smooth out the shocks which would have been caused by the rolling of the ship and any unevenness in the running of the winch. It was especially useful in indicating when bottom had been struck with the heavy Bigelow sounding tube.

(d) WATER BOTTLES.

For the shallower depths down to 150, and occasionally 400 metres, the standard Nansen-Pettersson insulating bottle was used, and worked perfectly satisfactorily. It was, however, found to be considerably slower in use than the reversing bottles, and its special valve was much less convenient for emptying than a simple tap would have been.

All the deeper samples were taken with Ekman-pattern reversing bottles of various types. The majority had been used on Sir Douglas Mawson's expeditions in the "Discovery" to the Antarctic, and were made by Messrs. Elliott & Garrood. The end plates, springs, and the insides of the barrels of three of them were plated with chromium before the Expedition in order to obtain samples uncontaminated with copper from the bottle. The chromium proved extremely resistant to sea-water. A further three bottles were specially modified by Messrs. Munro to take three instead of two thermometers, in

order to allow of the addition of one unprotected to the usual two protected ones. All these suffered from the slight defect that the bottle usually failed to lock into position in the frame when closed under water. This made it necessary to haul the bottle slowly through the water when heaving in, to avoid disturbing the thermometers. The defect appeared to be mainly a matter of balance, since bottles obtained later from Messrs. Munro, which were fitted with balance weights, hardly ever failed to work perfectly.

Of "messengers" two types were used. In one the top movable portion was locked in either the open or the closed position by a spring-loaded plunger; in the other it was simply held in the closed position by a spring. The latter type proved the more convenient in use, since it could be operated with one hand.

#### (e) THERMOMETERS.

The number of these used has already been recorded (Vol. I, p. 11). Nansen-Pettersson insulating bottles were used at most stations down to 150 metres, and in a few cases deeper. They were fitted with Schmidt protected non-reversing thermometers, which were found to be extremely satisfactory. Correction for adiabatic cooling has been applied in the few cases where it was significant. Owing to the rapid change of temperature with depth and the small temperature effect of the pressure at 150 metres, this was only rarely the case. Occasionally the temperature as determined in this way was checked by using reversing thermometers at the same depth; the results were in excellent agreement.

At greater depths protected reversing thermometers supplied by Negretti & Zambra were used, usually in pairs, while the lowest bottle of each haul carried in addition an unprotected thermometer for correcting the depth of observation. The readings of the protected thermometers have been corrected according to the formula and tables of Subow (1931), while those of the unprotected thermometers have been treated by the formula of Sverdrup (1933). Paired thermometers gave good agreement, the difference rarely exceeding  $0.01^{\circ}\text{C}$ . All thermometers were standardized by the National Physical Laboratory both before and after the expedition.

### METHODS OF ANALYSIS.

#### (a) SALINITY.

The halogen content of water samples was determined by the method of Oxner and Knudsen (1920). After a little practice this method can be used with machine-like precision and speed. Frequent titrations of "normal sea-water" supplied by Knudsen were used as a check, and duplicate samples analysed. It was found that a blue "daylight" bulb greatly increased the ease of determining the end-point of the titration. The more mechanical the method became, the more accurate were the results obtained.

The titration values were corrected to halogen, and these to salinity and  $\sigma_0$  by the tables of Knudsen (1901);  $\sigma_t$  was calculated from the tables of Matthews (1932). The calculation of anomalies for dynamical computation of water movement was made from the tables of Sverdrup (1933b).



(b) OXYGEN.

Dissolved oxygen was determined by a modification of Winkler's method described by Jacobsen and Knudsen (1921). Manganous sulphate was used instead of the usual chloride, and was found to be less contaminated with iron. The sodium thiosulphate used for the titration was kept as a normal solution and diluted as required. The diluted solution (N/200) was allowed to stand, and then standardized by the iodate method (Alsterberg, 1926). Standardizations were repeated at frequent intervals, but it was found that the thiosulphate so prepared was remarkably stable, a variation of more than 0.2% in two days being very unusual, while this limit was never reached in a single day. At first some trouble was experienced owing to the "drift" of the end-point, but it was soon found that as the method became thoroughly mechanical this error was entirely eliminated. An ordinary electric bulb and a white porcelain plate under the bottle used for the titration was found better than daylight to work by. For collecting the samples glass bottles were used whose stoppers had been ground off at an angle, and a little experience with these made it quite easy to avoid enclosing bubbles of air. The bottles held approximately 120 ml., but their volumes were not determined; instead, samples of 50 ml. were withdrawn with a pipette for titration. This method saves a great deal of trouble in the calculations, and enables duplicate titrations to be made if desired.

The rather sudden and sometimes erratic variations in the amount of dissolved oxygen found led us to suspect the accuracy of our results, but it was found that duplicate samples gave results agreeing within the error of the titration. Even samples collected on different hydrographic hauls but from the same depth at the same station showed no significant disagreement. We therefore reached the conclusion that the methods of collection, bottling and determination were not at fault, but that oxygen does indeed vary in a rather erratic manner, probably on account of its biological reactions.

The percentage saturation was calculated from the salinity and temperature data with the aid of the table of Subow (1931).

For the determination of phosphate, nitrite and silicate a long tube-colorimeter of the type described by Sund (1931) was used. This instrument was modified by the substitution for its original 2-volt lamp of a 40-watt "daylight" lamp run from the ship's electrical system, and by the addition of an extra sheet of opal glass to the diffusing system. Of the two pairs of wedges supplied the cemented ones were the more satisfactory, as the built-up ones defied nearly all attempts to prevent their leaking. For nitrate estimations a Duboscq-pattern colorimeter by Leitz was used.

(c) PHOSPHATE.

Phosphate was determined by the method described by Sund (1931) and his colorimeter was used for the comparisons. The green colour frequently reported in operating this method did not appear often, but fading gave considerable trouble, probably on account of the high working temperatures. The difficulty of fading can be largely eliminated by standardizing the method both in the mixing and in the time allowed to elapse before comparison.

(d) SILICATE.

Samples were collected in waxed bottles and analysed, as described by Atkins (1926). The picric acid solution used as a standard had been previously standardized against a solution of known silicate content at the Plymouth Marine Biological Laboratory through the kindness of Dr. L. H. N. Cooper. In water from depths not exceeding a few hundred metres no difficulty was found with the determination. In such samples the colour of the picric acid solution is always slightly greener than that developed by the silicate. In some deep samples, however, usually of the order of 2000 metres, this colour difference was reversed, the picric acid solution being the yellower of the two. It is hoped to investigate this phenomenon later: at present the only suggestion that can be made is that it is due to the presence in the samples of some other substance such as iron.

(e) NITRATE, NITRITE AND AMMONIA.

The methods used were essentially those described by Wattenberg (1931) and Witting (1914), and are considered with the work of Mr. Gilson on the nitrogen cycle (Section 2 of this volume).

(f) HYDROGEN-ION CONCENTRATION.

This was determined by means of indicators and buffers, and the method will be discussed by Mr. Mohamed in his section on the subject. The results given in the tables have been corrected for salinity and temperature as described in that section.

ACKNOWLEDGMENTS.

It cannot be too strongly emphasized that this volume is the work of three persons, and the authors wish to give full credit to their colleague Mr. Mohamed. As well we wish to thank the whole ship's company for unfailing assistance.

The services rendered by the Hydrographic Department of the Admiralty were very great. Through the courtesy of the Hydrographer of the Navy, H.M.S.S. "Endeavour" worked several stations for us in the neighbourhood of Ceylon; Mr. D. J. Matthews also assisted wherever possible, both with advice and practical collaboration; lastly we have to acknowledge the loan to us of Lt.-Cmdr. W. I. Farquharson, R.N., to whose care and precision we owe the accuracy of our station positions and depth records, and to whom we are indebted for advice on innumerable points.

The Meteorological Office very kindly arranged for the collection of many surface samples and temperatures by ships of the Merchant Service, and we wish to record our gratitude to the officers who performed these duties so ably.

Through the courtesy of the "Discovery" Committee R.R.S. "Discovery II" carried out observations at a series of stations off the African coast, and for these we wish to thank both the committee and the officers who performed the work.

The kindnesses of the staff of the Plymouth Marine Biological Laboratory have been too numerous for detailed enumeration, but in particular we must thank Dr. E. J. Allen, C.B.E., F.R.S., Dr. W. R. G. Atkins, O.B.E., F.R.S., Dr. L. H. N. Cooper, Mr. H. W. Harvey and Mr. G. A. Steven for help both before and after the Expedition.

Professor Sverdrup, of the Geophysical Institute, Bergen, very kindly placed his vast experience of oceanography at our disposal.

For innumerable courtesies in Egypt we wish to acknowledge our gratitude to the Egyptian Coastguard Service and the Faculty of Science in the Egyptian University. Particularly helpful were Professor D. H. Bangham and Dr. H. Faouzi.

Finally and above all we wish to thank the John Murray Committee, and especially Professor J. Stanley Gardiner, without whose untiring efforts the Expedition would have been impossible.

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# THE NITROGEN CYCLE

BY

H. CARY GILSON, M.A.

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## I. INTRODUCTION.

ONE of the greatest difficulties in the study of the relation between marine organisms and their environment is the extremely close interrelation between biological factors. We cannot fully understand the plants without knowing all about the animals which feed on them, and the bacteria which dispose of their dead remains, any more than we can understand the animals apart from the plants and bacteria which form their food, or

the bacteria apart from the plant and animal residues which provide their energy. It was thus found impossible to study the nitrogen cycle without preliminary consideration of the factors which govern the productivity of the sea as a whole, and this forms the subject of the next section.

Sections III and IV represent attempts to approach the nitrogen cycle itself from two distinct points of view, the one by the method of laboratory experiment, and the other by the investigation of the conditions actually obtaining in the sea. For the latter, which came first in time, I was fortunate to have the opportunity of the cruise of the John Murray Expedition (in H.E.M.S. "Mabahiss") in 1933-34, and I am much indebted to Professor Stanley Gardiner for suggesting that I should undertake the study of the distribution of nitrogen compounds in the area investigated. After the return of the expedition, examination of the data obtained suggested certain problems, especially regarding the distribution of nitrite, which seemed as though they would repay investigation by laboratory experiments. With the kind permission of the Murray Trustees and of the authorities of Trinity College, Cambridge, these experiments were undertaken at the laboratory of the Marine Biological Association at Plymouth while holding the Cambridge University table there during the first four months of 1935. They were in some degree successful, and the results are reported in Section III. They have been put before the account of the work carried out during the John Murray Expedition because they help to some extent in elucidating it. As was bound to be the case in the short time available, they are only of a preliminary nature, and were intended partly to determine whether the method was in fact likely to yield results of value. They have shown the necessity for modifications, especially in regard to the part played by bacteria, but they have also shown that it is possible to obtain much information about the metabolism of phytoplankton organisms by the chemical analysis of cultures.

It will be observed in Section IV that the aspect most stressed is the phytoplankton. As the primary producers of organized living matter from inorganic materials, the photosynthetic forms of life are the logical starting-point for the investigation of the cycle. It is therefore from this point of view, rather than that of the oceanic circulation of water, that the John Murray Expedition results have been treated here. Similarly in all questions of productivity, it is the production of phytoplankton which has been primarily considered.

Finally in Section V an attempt has been made to survey present-day knowledge of the nitrogen cycle, especially the bacterial side of it, on the basis of recorded work both in the laboratory and at sea, and to draw such conclusions as are possible from the available data.

Quantitative investigations of the plankton were started by Hensen (1887), who was the first to show the seasonal variations which are now a commonplace of all investigations in temperate regions. Then the plankton expeditions (*vide* Hensen, 1887; Gran, 1912; Lohmann, 1920) demonstrated the far denser plankton population of coastal waters as compared with open sea. Two great problems had now presented themselves—the reasons for the greater productivity of coastal waters, and the factors controlling the spring plankton outburst, and almost all subsequent research on the subject has been directed towards the solution of them.

The earlier work was all done with nets of various types, and it was not until Lohmann introduced the use of the centrifuge that the importance of the very small organisms,



which escape even the finest nets, was realized. The method has been used since, especially by Gran and his collaborators, and has produced excellent results. It has the great advantage of giving an accurate estimation of the population density in the water at a known depth, but owing to the small volume of samples which can be examined, it does not always give a representative picture, if the plankton is sparse. The net has the advantage of filtering a larger volume of water, but there is always the difficulty of determining either the volume filtered, or the depth from which the contents came. It is the only method available for the larger zooplankton, and must in many cases be used in conjunction with the centrifuge. An improvement recently devised by Harvey (1934*a*) consists of an instrument mounted in the mouth of a fine silk net, which measures the volume of water which passes through the net. This, combined with the method used by Kreps and Verjbinskaya (1930) (see also Harvey, 1934*a*) of estimating the phytoplankton by its pigment content, provides a very useful rapid method of determining approximately the total phytoplankton content of the water. Another improved form of the larger net is the serial closing net of which a set is used on the American research vessel "Atlantis" (Clarke, 1933).

An important contribution to the problem was made by Brandt (1899, 1902, 1920), who showed that the nitrogen, and especially the phosphorus compounds, which are essential for the growth of the phytoplankton, are often present in sea-water in extremely minute amounts. He put forward the theory that the reason for the richness of certain areas and certain times of the year might be the presence of an abundant supply of these nutrient salts, which in other places and at other seasons might be available only in very small quantities, insufficient to support a dense plankton population. This theory, as we shall see, has been amply confirmed by subsequent work.

Brandt and Raben's work showed the value of chemical investigations to elucidate planktological work. It was, however, soon realized that the methods they used were not sufficiently sensitive for the purpose, and were far too laborious to allow of the accumulation of any great mass of data. Thus no great progress was made until a new phase was begun by the introduction by Atkins and Harvey of improved methods for the estimation of the very small quantities of phosphates and nitrates often present in sea-water. The results obtained at Plymouth from 1922 onwards (Atkins, 1923, etc.; Harvey, 1926, 1928*a*; Cooper, 1933) showed for the first time in a really satisfactory manner that there is a regular cycle in the amounts of nutrient salts present in the sea, which corresponds with the annual cycle of the phytoplankton. The great importance of combining chemical analysis of the water with counts of the plankton population is well shown by Braarud and Klem (1931), who reached considerably different conclusions from those previously drawn by Gran (1923, 1927, 1929*b*, etc.) and his colleagues from data obtained in the same area on the phytoplankton distribution alone.

The emphasis in recent years has thus been rather on the chemical aspect of the problem. This is well brought out by a comparison of the work done on the "Michael Sars" expedition in 1910 with that done on the "Meteor" expedition of 1925-28.\* Since the chemical method of approach still seemed the most likely to yield valuable results, the same is true of my own work on the John Murray Expedition. There I was allotted the task of carrying out all the analyses for nitrate and nitrite on the samples

\* See Murray and Hjort's book, 'Depths of the Ocean', and the "Meteor" reports still in process of publication.

collected. The expedition also had constructed a quantitative plankton net of the type designed by Harvey (1934*a*), of which I was put in charge.

I am much indebted to Dr. L. H. N. Cooper for help with the analytical methods and preparation of reagents before the expedition set out; to Dr. E. J. Allen, C.B.E., F.R.S., for help and instruction in the methods of culturing diatoms; and to Mr. H. W. Harvey for advice with regard to the design and operation of the quantitative plankton net.

## II. THE CONDITIONS FOR THE PRODUCTION OF PLANKTON.

This whole question has been so frequently reviewed that there is no need to go into the data in any great detail. It is, however, necessary for the understanding of what follows to sum up briefly our present knowledge on the subject.

Since Brandt's (1905) first review of the problem the outlook has changed much. At that time the only knowledge available was of the actual distribution of plankton, and it is only in more recent years that improved methods of analysis have given the mass of chemical data now available. The theory he developed in his series of papers (1899, 1902, 1920), "Über den Stoffwechsel im Meere", that production was closely dependent on supplies of nutrient salts has been abundantly verified, and was again reviewed by him in 1929. This theory forms the basis of all modern work, and has been brought more up to date by Gran (1931).

### (*a*) PHYSICAL FACTORS.

The most important of these for the phytoplankton is light. Owing to absorption by the water and scattering by the particles suspended in it, the illumination falls off rapidly below the surface of the sea, so that there is only a comparatively narrow zone in which light is sufficient for photosynthesis. The thickness of this layer varies greatly with weather, season, and latitude, from *nil* in the polar winter to 100 metres or more in clear water and low latitudes.

Gaarder and Gran (1927) observed the changes in oxygen concentration in flasks of sea-water rich in phytoplankton suspended at various depths. This enabled them to determine the depth at which the oxygen produced by photosynthesis just balanced that consumed by respiration. This level, called the "compensation point", marks the lower limit of the zone in which effective phytoplankton growth is possible; in Oslo Fjord at the time of the spring diatom outburst it lay about 10 metres below the surface. Using diatom cultures instead of raw sea-water Marshall and Orr (1928) carried out similar experiments in Loch Striven, where they found the compensation depth to vary from 2 metres on a dark day in mid-winter to 30 metres on a bright day in summer.

The relation to light is complicated by the fact, first observed by Schimper (Karsten, 1905), that too much light is injurious to diatoms. This was verified by Marshall and Orr, who found that even in winter illumination is supra-optimal at the surface on a sunny day, while in summer the deleterious effect may at times extend 2 or 3 metres below the surface. Flagellates and Dinoflagellates are apparently not injured in this way by excessive light (Gaarder and Gran, 1927). Jenkin's\* similar experiments in conjunction with measurements of the illumination show that below the limit of this injury effect, photosynthesis bears a direct relation to the amount of light reaching any given level.

\* Personal communication from Miss P. M. Jenkin, whose paper is in preparation.



Atkins (1928) (*cf.* also Herdman, Scott and Dakin, 1910) suggested that in the winter in temperate regions lack of light limits the growth of phytoplankton, and that the spring outburst is conditioned by the increased amount of sunshine in March. Marshall and Orr (1928), on the basis of their experiments, consider this unlikely. They stress the great importance of length of day, and while admitting that light may be limiting in mid-winter, they remark (p. 340), “. . . it is difficult to believe that in the lengthening days of February and March light can act as a limiting factor for growth in the sea”. The same view is expressed by Føyn (1929), on the ground that Atkins's theory does not explain the fact that the outburst on the Norwegian Coast begins exclusively near land. On the other hand Braarud and Klem (1931) have shown that there is no foundation in fact for the view put forward by Føyn and by Gran that the outburst in Norwegian coastal waters is conditioned by an increase in the supply of nutrient salts from land. They therefore return to the theory that the increasing amount of light in spring is one of the determining factors.

At the present time it is impossible to say whether this view is correct or not. The influence of illumination is much complicated by the fact that both sunshine and length of day have to be taken into account, and by the effect of stormy weather, which greatly increases the loss of light at the water surface. That light is not always the key factor is shown by the fact that the spring maximum occurs about the same time in the Gulf of Maine (Bigelow, 1926) as at Lofoten (B. Ruud, 1926) which is  $18^{\circ}$  farther north. Also W. E. Allen (1927) found no correlation between light and the phytoplankton crop in California.

Whatever the importance of light in relation to the spring outburst, it certainly does limit the thickness of the productive layer in all but very shallow water; its lack is also the reason for the sparse plankton found in winter in high latitudes.

As far as concerns the diatoms, which form the most important element of the temperate phytoplankton, temperature appears to have little influence, abundant growth being possible over a range from  $-1.5^{\circ}$  to  $30^{\circ}$  C. Low temperature never seems to limit production, and indeed the Norwegian workers, Gran, Braarud, Føyn and others, have shown that the spring outburst off their coasts commonly begins when the sea-temperature is at its minimum for the year ( $0 - 5^{\circ}$  C.).

Ostwald (1902) has pointed out that a low temperature may favour the plankton owing to the higher viscosity of the water, which enables the organisms to remain for a longer period in the photosynthetic zone. The importance of viscosity is very hard to estimate. That diatoms do sink after a period of rapid growth has been observed by Marshall and Orr (1927), by Lohmann (1908), and by Gran (1915), who suggested that the increased rate of multiplication at a higher temperature might balance the increased rate of sinking. In the absence of any culture experiments in which illumination and temperature have been controlled, it is impossible to judge of the validity of this view. That sinking below the limit of adequate illumination is not the only, or indeed the main cause of the end of an outburst, is shown by the fact that similar sinking coincides with a fall in the growth-rate of a culture, where the illumination is unaffected (see below, p. 38).

Although temperature does not appear ever to limit the production of plankton, it undoubtedly does affect its composition. Some species of diatom are judged from their occurrence to be thermophile; the Dinoflagellates in temperate waters always have their



maximum in the warmer conditions of July and August.\* Conversely, the Coccolithophoridæ, so characteristic of tropical oceans, are never found where the temperature is low; thus in the Gulf of Maine Braarud (1934) records that *Pontosphaera huxleyi* was confined to water with a temperature above 10° C.

By far the most important effect of temperature is its indirect one on the density of the water. The difference in density between the surface layer warmed by the sun and the cooler water below prevents mixing across the boundary, so that the surface layer is cut off from all possibility of renewal of its nutrient salts from the rich stores in the deeper water. As may be clearly seen in the stations worked in the Gulf of Aden by the John Murray Expedition, and described below, such a boundary may also prevent the utilization of the nutrient salts in the water immediately below it, even though the illumination may be adequate. This is due to the growing cells being held up at the boundary, unable to sink below it until after their active life is over.

On the other hand, the development of stably stratified conditions may have an important effect in promoting the growth of the plankton. As we shall see in discussing the chemical factors, vertical mixing at some time of the year is often the most important factor in determining the productivity of an area. While active mixing is in progress, no great plankton development can occur, because the growing diatoms are so rapidly carried down below the limit of adequate illumination; thus a sufficient stock can never be accumulated near the surface to counteract wastage, and start a vigorous production. This effect appears both off the Norwegian coast (Braarud and Klem, 1931), and in the Antarctic Ocean (Gran, 1931, and J. T. Ruud, 1930). In both cases the stratification is not due to warming of the surface water, but to the advent of a surface layer of lower salinity, in the first case from the rivers, and in the second from melting ice.

#### (b) CHEMICAL FACTORS.

Of the many constituents of sea-water the most important for the plankton are the nitrates and phosphates, and it is on the supply of these that the productivity of an area principally depends. Such a supply may be brought to the surface layers in several ways, which produce corresponding variations in the resulting type of plankton production.

During a period of production a continuous hail of dead plankton, both plant and animal, carries both substances down out of the illuminated zone to the bottom, where bacteria return the phosphorus and nitrogen to solution as phosphate and nitrate. In stable water conditions, such as are found nearly everywhere in summer, they remain there as a rich bottom layer. But with the approach of winter in temperate and polar regions, the surface layers of the sea cool, and consequently rise in density. Unstable conditions are thus set up, and helped by the wind, the whole body of water turns over, becoming homogeneous from top to bottom. Owing to insufficient light at this season, the supplies of nutrient salts thus brought up remain unused till the spring. With the

\* As pointed out by Gran (1929b), their presence at this time of year in conditions which will not support any considerable diatom population is connected with the fact that owing to their mobility and their lower growth-rate (Apstein, 1910), they can make use of far more scanty supplies of nutrient salts. It has been supposed that diatoms and dinoflagellates are mutually antagonistic, but this is not supported by Sleggs (1927). The scarcity of dinoflagellates in spring in European waters is almost certainly due to the low temperature, and not to the presence of abundant diatoms.

increasing daylight of March production begins, and rapidly develops into an enormous outburst, mainly of diatoms, which continues until the end of April. In shallow seas such as the English Channel, where there is considerable tendency for mixing by wind and tide, almost the entire nutrient salt content of the water column can be used up by the plankton. Much of it is consumed in the spring outburst, but considerable production occurs during the summer, until in August the development of a marked thermocline cuts off the supply from below. The rapid fall in the phytoplankton population after the spring outburst is attributed by Harvey (1934*b*) to an increase in the herbivorous zooplankton (see also Harvey, Cooper, Lebour and Russell, 1935).

In very shallow water, such as the Limfjord in Denmark (Ostenfeld, 1913), mixing by convection can occur all the year round owing to heating of the bottom by the sun. Here there is also the possibility of supply of nutrients from land, and a rich plankton therefore persists throughout the summer.

In the deeper water of the Scottish lochs and the Norwegian fjords vertical circulation is only possible for a short time in winter, since the influx of fresh water with the spring rains and the melting of the snows leads to stable conditions early in the year. The supplies brought to the surface by the winter mixing are rapidly used up by the diatom outburst in March and April, and plankton is sparse during the summer and autumn. In some places an irregular supply from land produces a series of minor plankton maxima during the summer months\* (Marshall and Orr, 1927 ; Gran, 1929*b*).

In the warmer parts of the world mixing by convection never takes place. In certain areas, however, a continuous supply of nutrient salts is made available by the upward movement of water from the depths. This may occur where a deep oceanic current is deflected by a submarine bank, or where an uneven bottom tends to cause turbulence. The rich plankton produced over the Faeroe Bank from this cause was observed by Paulsen (1909) and Gran (1929*a*), and persists throughout the summer. Similar conditions occur in Puget Sound, where the strong tidal streams running in narrow straits of varying depth result in abundant phosphate and diatoms all through the summer. Alternatively supplies may be brought up by the "upwelling" which occurs along a coast to replace surface water driven out to sea by an off-shore wind. This occurs particularly in the Trade Wind belt on the west coasts of both Africa and America, where it results in continuous rich production. According to Moberg (1928) the plankton off the Californian coast is mostly between 20 and 40 metres down, and he suggests that it is limited above by lack of nitrate and phosphate, and below by lack of light. Hentschel and Wattenberg (1930), in a study of the whole south Atlantic, show how upwelling near the African coast forms small areas which are rich in both phosphate and plankton ; round these are zones still rich in plankton, but in which the phosphate has already been consumed ; west of these again is a large area which is poor in both phosphate and plankton and extends south to about 30° S. Beyond this is another rich area where there is mixing by convection in the winter.

Over most of the tropical oceans, where there is no such source of supply, stable conditions arise, in which production is brought almost to a standstill by the lack of nutrient salts. In the equatorial region the removal of surface water in the currents set up by the trade winds causes a slow upward movement of deep water. Thus the regions

\* Harvey (1934*b*) is inclined to attribute the summer fluctuations of the phytoplankton to variations in the proportions of carnivores and herbivores in the zooplankton.



which are poorest in plankton lie from about  $10^{\circ}$  to about  $20^{\circ}$  on either side of the equator.

For plant growth another essential, which is present in very minute amounts in sea-water, is iron. Since it is only recently that adequate methods of analysis have been introduced, little is known as yet about its distribution in the sea. Braarud and Klem (1931) found values ranging from 4 to 23 mg. Fe/m<sup>3</sup> off Møre. There the surface water contained more iron than deep water, and the fjord more than the sea outside, owing to the influx from a river. Some of the iron is retained by a Gooch crucible, and evidence is put forward that some of it is in the form of colloidal ferric hydroxide.

Thompson, Bremner and Jamieson (1932) found on the other hand that the iron content rose with depth. The amount present in the San Juan Archipelago region ranges from 60 mg. Fe/m<sup>3</sup> in March and April to a minimum of 32 mg. Fe/m<sup>3</sup> in July. Lower concentrations were found in the photosynthetic zone, indicating its consumption by the plankton. In a later paper (Thompson and Bremner, 1935) the iron content of the open water beyond the continental shelf is reported to range from 11 to 45 mg. Fe/m<sup>3</sup>. Of this about half is in an "insoluble" form retained by fine grain filter-paper. According to Cooper (1935*b*) an even smaller proportion (probably not more than 2 mg. Fe/m<sup>3</sup>) is in true solution and capable of passing a membrane filter. He also reports that the iron content of phytoplankton is approximately four times the phosphorus content, so that the demand for iron during an outburst must be very great. Thus on one occasion as much as 16% of the total iron present was in the plankton. Since according to his calculations the solubilities of ferrous and ferric ions in sea-water are both exceedingly small (of the order of  $3.5$  and  $10^{-12}$  mg. Fe/m<sup>3</sup> respectively), it is difficult to see how the plankton organisms obtain their supplies. Evidently much of the iron present must be in the form of stable complexes, such as ferri-fluoride, and a further large fraction is apparently in a colloid-disperse state.

Of the source of supply very little is known. Considerable quantities, mostly in an insoluble form, may be brought down by rivers; 67 mg. Fe/m<sup>3</sup> were found in the waters of the Rauma by Braarud and Klem, and 1250 mg. Fe/m<sup>3</sup> in surface water near the mouth of the Fraser River by Thompson and Bremner. Most of this is probably in the form of the basic carbonate. Some may go into solution and become available for the phytoplankton, but much of it probably sinks unchanged to the bottom. In any case most of it is probably hydrolysed sooner or later to the insoluble hydroxide, and is thus permanently removed from the circulation. Whether any iron is brought up from the depths with the nitrate and phosphate is unknown, but the high iron content of many deep-sea deposits makes this seem unlikely. It is possible that we have a clue to the source of supply in Cooper's (1935*b*) observation that the iron content of zooplankton is very much less than that of phytoplankton. This corresponds with his further observation that animal faecal pellets are especially rich in iron, containing about five times as much iron as phosphorus. It is therefore probable that the iron is returned to circulation more rapidly than is the phosphorus, and so may complete the cycle more than once in the year, as is apparently the case with silica (Cooper, 1933). It is thus possible that the apparently inadequate supplies may yet suffice for the requirements of the plankton.

The importance of iron to the plant is connected with the formation of chlorophyll. Thus Emerson (1929) and Fleischer (1935) varied the chlorophyll content of *Chlorella vulgaris* by varying the iron content of the culture medium. In culture experiments with



raw plankton (Gran, 1931, 1933), the addition of iron in various forms usually gave better growth than controls enriched with nitrate and phosphate only, especially in the case of neritic species of diatom grown in oceanic water. Similarly Harvey (1933), working with cultures of *Nitzschia closterium*, found that the addition of 1 mg. Fe/m<sup>3</sup>, as ammonium ferri-citrate, approximately doubled the growth-rate. The ferri-citrate complex is not apparently immediately available to the diatoms, and it is suggested that they depend on ions given off "which escape hydrolysis to the unavailable hydroxide". Analysis failed to detect any ferrous or ferric ions until the sea-water had been acidified and vigorously oxidized, and Harvey concludes that there is probably less than 1 mg. Fe/m<sup>3</sup> present in a form immediately available to the plankton, though more apparently becomes available as this is consumed.

The question of the effect of iron is bound up with the fact, long known, that the growth of various plants and algæ in culture is accelerated by the addition of an extract of soil or vegetable matter (E. J. Allen, Miquel, Schreiber and others). This has been supposed to be due to an addition to the available iron supply. However, Harvey (1933) showed that even if soil extract does add to the available iron, which is not always certainly the case, it also has some other independent stimulant effect. This is supported by the observation that an alkaline extract of soil is more effective than an acid one, Evaporation and ashing of the extract destroyed its growth-promoting properties, and Harvey suggests that these depend on some organic compound.

The isolation and synthesis of a plant growth substance or "auxine" ( $\beta$ -indolyl-acetic acid) by Kogl, Haagen-Smit and Erxleben (1934) suggests that this may be the compound concerned. This substance is known (Kogl and Haagen-Smit, 1931; Kogl, 1933) to be present in urine, and accordingly, at Mr. Harvey's suggestion, an experiment was tried to test this. A series of cultures of *Nitzschia closterium* abundantly supplied with nitrate and phosphate gave considerably more rapid growth in those flasks to which 0.1% of filtered and sterilized urine had been added, but the experiment was only of a preliminary nature and cannot be regarded as conclusive.

There remains one other chemical property of the water, which may influence the growth of phytoplankton. Barnes (1932) found that *Spirogyra* grew more rapidly in water which had been recently frozen than in water which had just been distilled, or had been long in the liquid state. He suggested that the trihydrone molecules present in the ice-water stimulated growth. This was tested on diatoms by Harvey (1933) with positive results in most, though not in all, experiments.

It is possible that any or all of these last three factors—iron, auxine, and trihydrone—may be the explanation of the apparently greater productivity of coastal waters as compared with the open ocean. This may, no doubt, be partly explained by the more effective winter mixing of the shallower water, but the nutrient salt supply is not a complete explanation of the phenomena of the Norwegian coast. It has been repeatedly observed (B. Ruud, 1926; Føyn, 1929; Gran, 1929*b*) that production starts close to the shore, and spreads out over the banks. This was attributed to the influx of water from land, which occurs with the melting of the snow. Braarud and Klem (1931) showed that the addition of nutrient salts from land by this means is insignificant, but their criticism that the big floods due to melting snow do not occur till May, when the plankton outburst is over, is not really to the point. There remains the possibility that the outburst is started off by the snow-water from low-lying land, as suggested by Gran (1923), not in

virtue of its content of nutrient salts, but because it brings trihydrone, iron, or auxine, or all three. There is also the probability already mentioned (p. 26) that the fresh water helps by promoting stability. Any one of these factors might be sufficient to explain the observed facts, but it is not unlikely that all three play a part in giving the fillip needed to start production. Once started, the outburst develops extremely rapidly in the favourable conditions, since growth is approximately logarithmic at first.

Owing to the abundant plankton found there in spring and summer, when most of the observations have been made, it has been generally supposed that the total annual production is much greater in high latitudes than in the tropics. On the basis of calculations concerning the western part of the tropical Atlantic, Seiwel (1935*a*) has thrown doubt on this view.

In the English Channel Atkins (1923) estimated from the phosphate consumption that the minimum total annual production was 1.4 kg. (wet weight) of phytoplankton per square metre of sea surface. Cooper (1933*a*) reached closely similar figures from the changes in CO<sub>2</sub>, oxygen, phosphate and nitrate. Kreps and Verjbinskaya (1932), again on a phosphate basis, calculated the minimal production in the Barents Sea to be between 2.9 and 5.6 kg. per square metre for the 100-day season. Seiwel's figure, recalculated on the same basis, is 4.64 kg. per sq. m. for the year, and he concludes that the area is more productive than anything found in higher latitudes, except perhaps the Arctic regions. This is attributed to the fact that production continues at an approximately uniform rate throughout the year. Comparison of this rate with those reported by various observers at the time of the northern spring outburst is interesting (Table I):

TABLE I.

Author.	Region.	Method of estimation.	Production rate. (grm./m <sup>2</sup> /day [wet wt.]).
Atkins (1923)	English Channel	CO <sub>2</sub> consumed	8.3
Cooper (1933 <i>b</i> )	" "	Various	8.3
Marshall and Orr (1927)	Clyde	O <sub>2</sub> produced	26.6
Gran (1927)	Bergen	"	6.7
" "	(Maximum figure in cultures)		25
Gran (1929)	Romsdalsfjord	O <sub>2</sub> produced	2.14-9.94 (5 stations).
Føyn (1929)	Lofoten	"	18.6
Kreps and Verjbinskaya (1932)	Barents Sea	P consumed	29-56
Seiwel (1935)	Tropical Atlantic	O <sub>2</sub> consumed	12.7

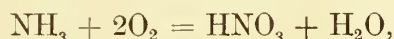
It will be seen that although his area is one which was found by Hentschel and Wattenberg (1930) to be distinctly poor in plankton, Seiwel's figure is higher than most of the estimates for the vigorous spring production in the English Channel and off the Norwegian coast.

There are several reasons for the discrepancy. Seiwel's estimate is based on a calculation of the annual oxygen consumption in the whole water column down to 2000 metres, especially the "oxygen-poor layer" between about 200 and 1200 metres (Seiwel, 1934). It is assumed that the oxygen so consumed represents the oxidation of the annual



crop of organic matter produced in the region in question. Now the water of the oxygen-poor layer is water which left the surface in high latitudes beyond 40° S. or 50° N., and is moving towards latitude 15° N. at about 200 miles per year. The assumption, therefore, that the oxidizable organic matter present has originated in the region under discussion seems a little doubtful. We have no data on the time taken for the complete breakdown of organic matter in the sea. The English Channel data, showing apparently complete regeneration of phosphate and nitrate each autumn, are inconclusive, since regeneration is continuous at the bottom, and we have no means of knowing that the phosphorus and nitrogen liberated each autumn is the same as that which was consumed in the surface layers during the preceding summer; there may be several years' stores awaiting bacterial action on the bottom. However, even if, as is probable,\* regeneration is completed within the year under those conditions, it does not follow that it is equally rapid in the water under consideration here. The regeneration process is known to be most rapid near the bottom, and as the water on which Seiwel's calculation is based has never been in contact with the bottom, decomposition may be very much slower. It is thus possible that a proportion at least of the organic matter oxidized has come with the water from elsewhere.

Another assumption involved in the calculation is that all the oxygen consumed has been used in the oxidation of carbon. This is certainly not the case, and in calculating the organic matter represented, allowance should be made for the oxygen consumed in oxidizing ammonia to nitrate. Since—



each atom of nitrogen requires 2 molecules of oxygen, whereas each atom of carbon only requires 1 molecule. Now plankton contains approximately 1 atom of nitrogen for every 7 of carbon, so that approximately 20% of the oxygen consumed is required for the oxidation of nitrogen compounds. The relation is only an approximation, since we cannot be certain that all the combined nitrogen is converted to nitrate at the same time as the carbon is oxidized to  $\text{CO}_2$ . If we apply this correction to Seiwel's figures we obtain 3.7 kg. (wet weight) per square metre as the total annual crop, and 10.2 gm./sq. m. for the daily production.

This is still unexpectedly high. The reason is probably that the figures quoted for more northern latitudes are all too low. Seiwel's method of calculation from the oxygen consumption gives a maximal value for the organic production. All the other methods—oxygen production,  $\text{CO}_2$  consumption, and phosphate consumption—give minimal estimates, since no allowance is made for simultaneous oxygen consumption (by zooplankton, bacteria, and by the phytoplankton itself) or regeneration.† It has been suggested (Føyn, 1929) that the resulting estimate of the total crop may be as much as 100% too low, and Gran's (1927) figures for the production in cultures tend to support this view.

Since the data for the two regions is by no means comparable, the comparison between the two is of doubtful value. We are, however, probably justified in concluding that, while the area investigated by Seiwel, which is fairly typical of tropical oceans, is rather

\* Cooper (1935a) finds that phosphate is rapidly and completely liberated from zooplankton material *in vitro*, while the process is very much slower and incomplete in the case of phytoplankton.

† A tentative correction for regeneration has been applied by Kreps and Verjbinskaya to their figure quoted above.



more productive than has been commonly supposed,\* it is considerably less so than the rich areas off the Norwegian coast and in the polar oceans, and not very different from the English Channel. Probably the most productive regions of all are the upwelling areas in the tropics.

### III. CULTURE EXPERIMENTS.

An attempt was made to gain some insight into the changes to be expected in the sea by studying the metabolism of phytoplankton organisms, using "persistent cultures"† of plankton diatoms (Allen and Nelson, 1910; E. J. Allen, 1914; Schreiber, 1928).

Some cultures were obtained by picking out small numbers of cells or chains from "very fine" tow-nettings with fine sterile pipettes under a binocular dissecting microscope. These were washed in one or more watch-glasses of sterile sea-water, and then transferred to a flask of culture medium. Another method used is to "plate" 0.5 to 1.0 ml. of tow-netting in about 20 ml. of culture medium in a Petri dish, which is then placed in a good diffuse light in a place free from vibration. Examination under the binocular microscope after 3 or 4 days will usually show a number of small colonies of diatoms, which can be picked out with pipettes, and transferred to culture flasks. (For further remarks on this method see Allen and Nelson, 1910).

By these methods the following species were obtained in culture between January and April, 1935:

*Biddulphia regia* M. Schultze.

*Asterionella japonica* Cleve & Möller.

*Coscinodiscus subbulliens* Jörgensen.

*Ditylium Brightwelli* (West).

*Lauderia borealis* Gran.

*Chaetoceros curvisetus* Cleve.

*C. affinis* Lauder.

*C. teres* Cleve.

*C. decipiens* Cleve.

Of these, *Biddulphia regia*, *Lauderia borealis*, *Chaetoceros curvisetus* and *C. decipiens* were found the most suitable for the purpose of experiment, being vigorous growers and fairly easily counted. *Asterionella japonica* also grew well, but proved impossible to count satisfactorily. *Ditylium Brightwelli* would have been an admirable subject, but the culture was obtained too late for any use to be made of it.

The cultures were grown in a north window, the row of flasks resting on a strip of mirror to give better utilization of the rather scanty winter light. Under these conditions, even in the short days of January, growth rates of the order of one division in 48 hours were observed at a temperature of 10–12° C. In the better light of March and April, when the temperature had risen somewhat (12–15° C.), growth was very much more rapid, and subculturing every three or four days was required to prevent the cultures becoming too dense and unhealthy.

\* Seiwel's (1935b) recent calculations of the eddy transfer of phosphate through the thermocline, which have just come to my notice, help to explain this, and show that the discontinuity layer is not so complete a barrier as it has been thought to be.

† "Persistent culture" is the term used by E. J. Allen to describe a culture which will give healthy subcultures and contains one species of diatom and no other organisms except bacteria, which are always present.

The culture medium found most satisfactory was a modified "Miquel sea-water" (Allen and Nelson, 1910), in which nitrate was reduced to give the ratio  $N : P_2O_5 =$  approximately 2.5 : 1. Schreiber (1928) remarks that excess nitrate tends to favour the bacteria, and there is no obvious advantage to the diatoms in the enormous excess of nitrate in the original medium. Clean sea-water passed through a Berkfeld filter, enriched with suitable amounts of nitrate, phosphate and iron and sterilized, was tried, but did not give such satisfactory cultures. This is in agreement with E. J. Allen's (1914) findings, where he suggests that the precipitate formed by the Miquel solution has some purifying effect on the water, which makes it a more favourable medium for the growth of diatoms.

The small stock cultures (50–100 ml.) were far too small for experimental purposes, and the Miquel culture solution is too rich in nitrate and phosphate to permit of accurate determination of the small changes produced by the growth of the diatoms. Also conditions in these cultures were quite unlike anything ever found in the sea.

For experimental purposes, therefore, 3-litre flasks were filled with clean sea-water, which had been passed through the Berkfeld filter. By blowing alveolar air through the water the pH was brought down to about 7.3, and the water was then sterilized, either by bringing it just to the boil, or by keeping it at 70°–80° C. for at least an hour. The  $CO_2$  lost in this process brought the pH back to the neighbourhood of 7.8. If the preliminary adjustment was omitted, it was found that the pH after sterilizing was usually 8.4–8.5, which is much higher than is ever found in the open sea. After cooling, the flasks were inoculated with from 20 to 50 ml. from a stock culture, the whole well shaken, and a sample immediately withdrawn for counting and analysis. The enrichment added with the inoculation usually brought the nitrate and phosphate of the experimental culture to values just above the winter maxima for the English Channel. Subsequently at varying intervals over periods up to 39 days the cultures were vigorously shaken, and samples of 100 to 150 ml. were poured off. In a portion of this the diatoms were counted; other portions were used for analysis for nitrate, nitrite and phosphate. (For the analytical methods used, see Appendix.)

The results, calculated to show the changes in successive periods, are given in Table II, and the actual changes in the composition of the medium in two typical experiments are shown graphically in Text-fig. 1.

Quantitatively the results are a little disappointing in that the rate of consumption of nutrient salts proved so very variable. This seems to indicate that not too much reliance must be placed on previous calculations based on a single set of analyses (*cf.* Atkins, 1923). The variability of the  $N : P$  ratio is probably due partly to the bacteria in the culture, and partly to the fact that nitrate is not the only source of nitrogen available. The fact that there were such large variations in the ratio of nitrogen and phosphorus consumed, as well as in the actual rates of consumption, indicates that the bacteria were probably the primary cause, rather than variations in the rates of consumption by the diatoms.

There remains, however, one observation concerning the nitrogen metabolism of the cultures, which is of great importance, especially in its bearing on the distribution of nitrogen compounds found in the sea. In the earlier stages of the cultures the concentration of nitrite was rather variable, and presumably depends mainly on the balance between the various kinds of bacteria present. But in all cases, when the culture began to die off, large quantities of nitrite appeared. The question of the origin of this nitrite will be



TABLE II.

Period. (Days of experiment.)	Production. (Millions of cells per litre.)	Nitrite. Change in concentration. ( $\gamma$ N/litre.*)	Nitrate-N.		Phosphorus.		N:P ratio. (Atoms N per atom P.)
			Fall in concentration ( $\gamma$ N/litre.)	Consumption. ( $\gamma$ -atoms per million cells.)	Fall in concentration. ( $\gamma$ P <sub>2</sub> O <sub>5</sub> /litre.)	Consumption. ( $\gamma$ -atoms per million cells.)	
Experiment A. 14.ii to 22.iii.35. <i>Chaetoceros curvisetus</i> Cleve.							
0-4	..	-0.2	45	..	12.2	..	18.7
4-11	1.45	+1.0	15	0.74	9.8	0.095	7.78
11-19	2.49	+0.3	44	1.26	9.0	0.051	24.7
19-25	(decrease)	+10.1	133.5	..	2.0	..	(338)
25-36	..	-7.0	18.5	..	3.0	..	(31.3)
4-19	3.94	..	59	1.07	18.8	0.067	15.9
19-36	..	..	152	..	5	..	(154)
0-36	..	..	256	..	36	..	(36.1)
Experiment B. 22.iii to 17.iv.35. <i>Lauderia borealis</i> Gran.							
0-7	0.642	+3.0	85	9.42	12	0.264	35.7
7-11	1.000	-2.6	11.6	0.828	22.5	0.317	2.61
11-17	0.540	-0.19	5.33	0.705	14	0.367	1.92
17-21	0.040	+0.2	4.5	..	-0.5	..	..
21-26	(decrease)	+0.85	1.0	..	-0.5	..	..
0-17	2.182	..	98.5	3.38	48.5	0.313	10.8
0-26	..	..	104	..	47.5	..	11.9
Experiment C. 29.iii to 17.iv.35. <i>Lauderia borealis</i> Gran.							
0-4	0.195	-1.1	8	2.93	2.6	0.187	15.6
4-10	0.684	-2.4	69	7.21	16	0.33	21.8
10-14	0.680	-0.35	38	4.0	13	0.27	14.9
14-19	..	+1.75	-0.9	..	-0.1	..	..
0-14	1.56	..	115	5.26	31.5	0.285	18.5
0-19	..	..	114	..	31.4	..	18.4
Experiment D. 29.iii to 17.iv.35. <i>Chaetoceros decipiens</i> Cleve.							
0-4	0.367	-0.06	2	0.390	11	0.422	0.92
4-10	0.751	-4.0	86	8.21	14	0.276	29.8
10-14	0.240	+0.2	30	8.93	8	0.465	19.2
14-19	(decrease)	+1.5	3.6	..	1.6	..	12.5
0-14	1.36	..	118	6.20	33	0.342	18.2
0-19	..	..	121.6	..	34.6	..	17.6

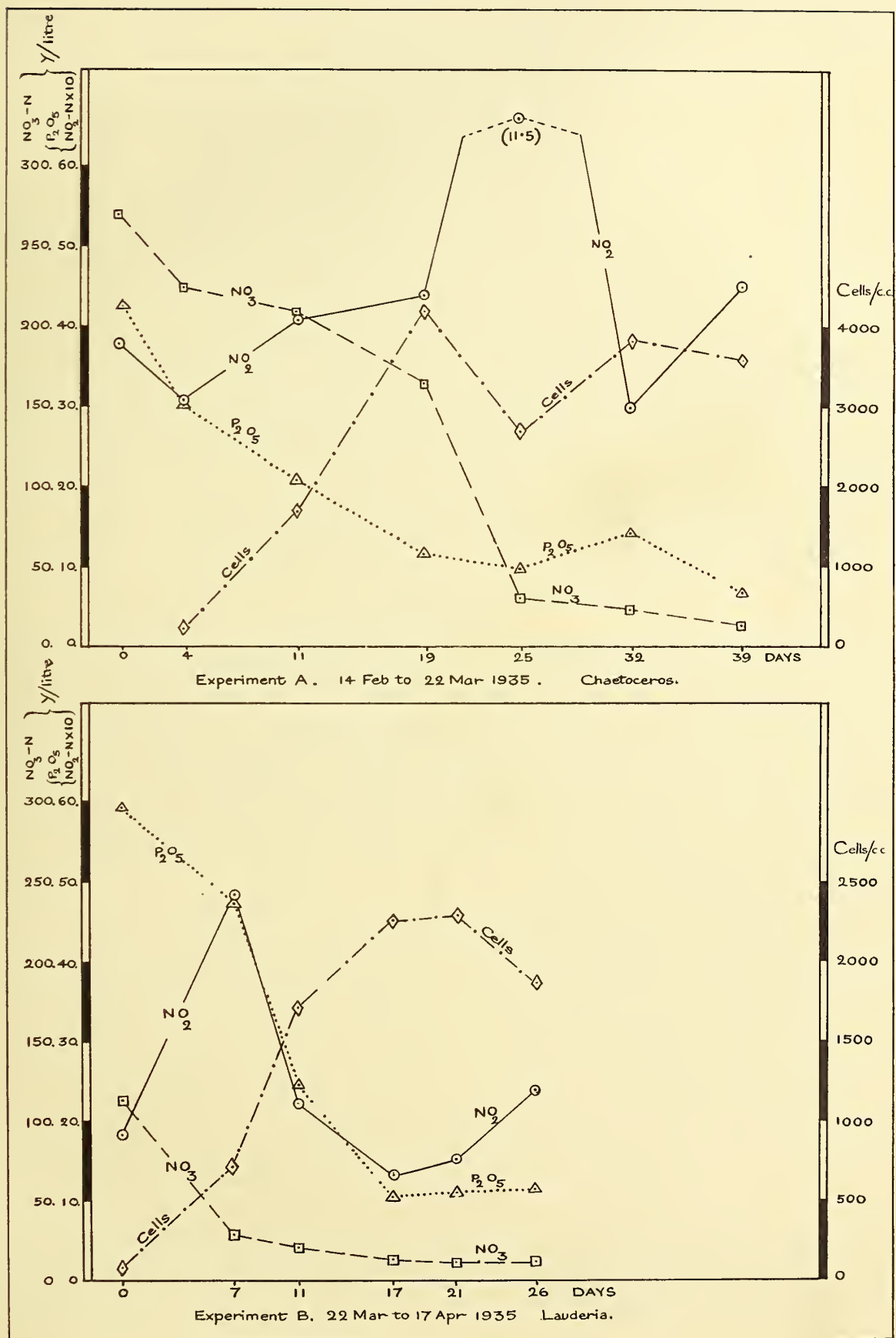
$\gamma$  = millionths of a gramme;  $\therefore \gamma/\text{litre} = \text{mg./m}^3$ .

$\gamma$ -atoms =  $\gamma$  divided by the atomic weight of the element in question (see Cooper, 1933d).

discussed later when we come to consider the nitrogen cycle in detail. For the present the important point is the connection which appears to exist between its appearance and the death of plankton organisms.

In those of the culture experiments which were continued long enough (*e.g.* Experiment A, Table II, and Text-fig. 1), the nitrite, after its sharp rise, showed a rapid fall. This





TEXT-FIG. 1.

corresponds well with the very sharp peaks in the nitrite profiles observed in the sea, and suggests that we are dealing with the same phenomenon.

#### IV. THE RESULTS OF THE JOHN MURRAY EXPEDITION.

##### (i) THE INTERPRETATION OF CHEMICAL RESULTS.

Before going on to discuss the results of the investigations carried out at sea, it will be necessary to consider a few points involved in their interpretation. The importance of chemical investigations as an aid to the understanding of an observed distribution of phytoplankton has been emphasized by Brandt, and many of the conclusions drawn from his and subsequent work have been summarized in Section II. The value of the combination has been well illustrated by Braarud and Klem's (1931) investigations off the coast of Norway, by Moberg's (1928) paper on the effect of upward water movements, and by Hentschel and Wattenberg's (1930) work in the South Atlantic. An attempt has, however, been made in the following pages to make an even fuller use of the knowledge gained not only at sea, but from cultural experiments, and for this purpose further discussion of certain aspects of the problem is necessary. It should be emphasized that the inferences here drawn from the chemical data are largely theoretical, and are as yet unconfirmed by direct observation.

##### (a) *Oxygen.*

The depth at which the oxygen produced by photosynthesis just balances that consumed by respiration has been called by Marshall and Orr (1928) the "compensation point". This depth will clearly vary from moment to moment with the varying amount of light reaching the water surface and penetrating the water, but for our purpose the important level is the balance level for the 24 hours, since this must mark the limit below which light is insufficient for continued growth of the phytoplankton. Gran found it in Woods Hole Harbour in August, 1932, at about 6 metres, when simultaneous measurements by Clarke and Oster (1934) of the penetration of light show that the illumination at this depth was approximately 1.5% of that at the surface. The sea on this occasion was calm and the sky clear.

Now, although the compensation point is not the depth at which the illumination is reduced to a particular fraction of that at the surface, but rather the depth at which it is reduced to a particular absolute value,\* yet in dealing with the clear skies and uniform conditions of the Arabian Sea during the NE monsoon, we may take as an indication of the depth of the compensation point that depth at which the light is reduced to about 1.5% of its surface value.

Poole and Atkins (1929) have shown that we may use the Secchi disc reading as a measure of the opacity of the water according to the relation—

$$\dagger\mu = \frac{1.7}{D} \quad (D = \text{the Secchi disc reading in metres}).$$

\* Pettersson, Hoglund and Landberg (1934) found this value to be about 400 lux for mixed plankton.

† This quantity has various names and symbols in the literature. Atkins also calls it both  $\lambda$  and  $\mu_v$  at different times. It has the names "absorption co-efficient", "transmissive exponent" (Clarke and Oster) and "extinction co-efficient" (Pettersson).

Now the illumination at depth  $d$  metres is obtained from the extinction co-efficient by the relation—

$$\mu_{0-d} = \frac{\log_e 10}{d} [\log (100 - s) - \log p_d],$$

where  $\mu_{0-d}$  is the extinction coefficient of the water layer 0 –  $d$  metres,

$s$  is the percentage of the incident light lost by reflection at the surface ;

$p_d$  is the percentage of the incident light which penetrates to the depth  $d$ .

It therefore follows that the depth at which the illumination is reduced to 1.5% of that at the surface is given by—

$$d = \frac{D \log_e 10}{1.7} [\log (100 - s) - \log 1.5].$$

In the very calm conditions usually prevailing, and with the sun at a considerably higher altitude, Poole and Atkins's average figure of 15% for  $s$ , the surface loss, is certainly too high for the Indian Ocean at the time of the expedition. They record a figure as low as 5% for one occasion in the English Channel. If we take the figure 5%, we obtain from the equation above—

$$d = 2.44 D.$$

In the absence of any data for surface loss or for surface illumination, we cannot determine the compensation level with any accuracy, but the value  $2.5 \times D$  will give us an approximate idea of the depth limit, beyond which photosynthesis is unlikely to balance the respiration of the phytoplankton.\*

If we started with homogeneous water 100% saturated with oxygen, and allowed plankton to grow in it, we should find after a time that the water below the compensation level lost oxygen, while that above it became supersaturated. In the sea, however, such ideal conditions are very seldom realized. Since the water is never 100% saturated when plankton production begins, and because there is always zooplankton present, the depth at which the water is just saturated can only very rarely be taken as indicating the compensation level.

In practice, then, we shall find that in the Indian Ocean the water at the compensation level, as indicated by the Secchi disc reading, is fairly constantly about 85–90% saturated, where there is a sufficiently thick layer of homogeneous surface water. Where the oxygen falls much below this value, it is safe to infer that conditions are not in equilibrium so far as concerns the relation between the plankton and light, often owing to some disturbing factor such as a sharp discontinuity layer. Such conditions occur for example in some of the Gulf of Aden stations (see Text-fig. 2). It must, however, be remembered that exact agreement is not always to be expected, since the determination of the compensation level from the Secchi disc reading is only an approximation. Thus Atkins's relation, quoted above, between the Secchi disc reading and the extinction coefficient is only an approximate one, and, secondly, the calculation involves the assumption that the transparency of the water below the point at which the disc disappeared is similar to that of the water above—an assumption which is not always justified.

\* Miss P. M. Jenkin tells me that in her experiments on the growth of diatom cultures in the sea (not yet published) she finds the compensation depth to be about 2.5 to 3 times the Secchi disc reading. It should be noted that most of her work was done at Plymouth in the long calm days of summer, when the compensation level for a given illumination is probably deeper than it would be in the tropics.



It will be observed that in a great number of the John Murray Expedition stations the Secchi disc-compensation level coincides with the lower limit of the layer of water depleted of nutrient salts—a good indication of its general validity. In hardly any cases does it fall above that limit; where it does, the reason may be either a general downward movement of the water, or a lack of uniformity in the transparency of the water, owing, for example, to a fresh plankton outburst in the upper levels.

The oxygen profile (% saturation plotted against depth) can tell us a great deal about conditions at any given station, especially when considered in conjunction with other data. Owing to the presence of phytoplankton, and to the possibility of direct gaseous exchange with the air, the surface layers are never very far from saturated with oxygen, unless they consist of water which has recently come up from the dark depths. But at a few metres below the surface, unless there is strong mixing by wind, the oxygen content depends on the balance between production by phytoplankton, and consumption by zooplankton and bacteria. A high oxygen will therefore indicate vigorous production of phytoplankton, and this may lead to a high degree of supersaturation during the enormous spring outburst of the temperate and polar regions (*e. g.* Gaarder and Gran, 1927, etc.). Supersaturation is not very common in tropical regions (apart from peculiar localities such as the shallow water over coral reefs), but may be seen occasionally (*e. g.* Stations 31 and 173.\* The oxygen curve frequently shows a maximum value well below the surface. This is due to the fact that the light is often too intense at the surface (Marshall and Orr, 1928), so that the zone of maximum productivity lies deeper. The plankton diagrams (*e. g.* Stations 130, 132, 167, 169,† Text-figs. 12 and 13) show that where such a peak is present, it usually occurs at a level just above that of the plankton maximum. Exactly the same relation can be seen in the recorded results of other workers, *e. g.* Gran (1929b, 1930, 1933), Gran and Thompson (1930), Gaarder and Gran (1927), Braarud and Klem (1931), Braarud (1934), so that we may conclude that it is commonly the case.

As to the reason for this we have no conclusive evidence, but there are several possible contributory factors. In the first place all the phytoplankton organisms enumerated by counting, or estimated by their pigment content, are not necessarily in an actively growing condition. This is borne out by the fact that it is not by any means every diatom picked out from the plankton which will grow in culture. It was repeatedly observed that when a single cell or a very small number of cells of a species was found in a tow-netting, no culture could be obtained of that species, while a species which was abundant in the plankton would nearly always give vigorous cultures. It follows that the total population is not necessarily a true measure of the productivity, if we define productivity as the rate of carbon assimilation and cell increase.

Now it has been repeatedly observed (Marshall and Orr, 1927; Gran, *passim*; Føyn, 1929) that after a period of activity diatoms and other phytoplankton stop growing and sink. This can also be observed in the laboratory, for in a young culture the cells remain well in suspension in the medium, whereas when the culture is several days old and contains

\* It may in fact occur more often than it is recorded, since the fact of supersaturation greatly increases the difficulty of avoiding loss of oxygen between the time of collecting the sample and the time of adding the Winkler reagents. This difficulty is considerable in the high air temperatures of the tropical day.

† Here although the maximum recorded is for the 0–40 m. layer, this was probably due to a very dense population at the bottom of this layer.

a dense population, the cells sink to the bottom of the flask, and little, if any, further growth occurs. This happens although the cells may be still healthy and normal in appearance, and will give further good growth on subculturing. In the sea, then, the population at any level in the illuminated zone consists partly of cells which are growing and dividing, and partly of cells which are senescent and merely sinking, and as we go downwards the proportion of growing cells will decrease, as will their actual numbers. The senescent cells, on the other hand, will not only increase in proportion to the growing ones, but also in total numbers, until the compensation point is reached. We shall therefore expect to find the densest population below the level at which multiplication is most rapid to an extent which will depend on the rate of sinking. Furthermore, any change in the density gradient of the water itself will affect the observed phytoplankton distribution through its effect on the rate of sinking of the dead and dying organisms; in particular a rise will tend to cause artificial plankton maxima. To sum up, then, the phytoplankton maximum may not necessarily be taken as indicating the level of maximum productivity, which is more accurately given by the oxygen saturation curve. In water where the density gradient is approximately uniform and fairly small, the plankton maximum will be expected to occur somewhat below the oxygen maximum.

Since the oxygen produced by photosynthetic organisms is merely a by-product of carbon assimilation, its production is always associated with the consumption of the nutrient salts (especially nitrate and phosphate) which are also necessary for the construction of the plant body. It is therefore to be expected that in stable conditions, where the composition of the sea-water is largely determined by the activities of the plankton, the profiles of oxygen and nitrate content will be mirror images. In a great number of cases this relation is found to hold with remarkable accuracy, as may be seen from the diagrams (*cf.* also Redfield, 1934). Where the relation does not hold we may infer the operation of disturbing factors, and comparison with other chemical properties of the water makes possible various deductions about the conditions. Thus high oxygen may accompany comparatively high nutrient salt concentrations. This indicates the early stages of plankton production, when considerable amounts of oxygen have already been liberated, but the limit set by the supply of nutrients has not yet been reached. Such conditions are commonly found at the beginning of the spring outburst in temperate waters, and may be seen at Stations 136, 166 and 167, where it is therefore inferred that there has been a recent influx of unexhausted water from elsewhere. Conversely, the zone of more than 85% saturation may not extend quite down to the limit of the layer which has been depleted of nutrients. This is rather rare, and the depth discrepancy is never great, but it was found at Stations 32, 76, 92, 173 and 182. The depletion of nutrient salts shows that there had been a good growth of phytoplankton, but this had ceased, and given place to an abundant zooplankton, or more probably provided nutriment for a rich bacterial flora, which had consumed much of the oxygen.

#### (b) Nitrite.

Nearly all the stations show the presence at the lower limit of the nutrient-depleted surface layer of a narrow zone of water which has a high nitrite content, ranging up to about 20 mg. N/m<sup>3</sup>. Where, as is very often the case, this peak nitrite value also falls at a density boundary, it is even more pronounced than otherwise.

Similar accumulation of nitrite in the thermocline has been observed elsewhere—



*e. g.* Moberg and Fleming (1933) off Southern California, Robinson and Wirth (1934*b*) off Vancouver Island, Braarud and Klem (1931) off the Norwegian coast, Orr (1926) in the Clyde area. Soot-Ryen (1932) off the Norwegian coast found that nitrite maxima appear in the upper layers (0–100 m.) about the times of the spring and autumn plankton maxima, in each case moving down later to the bottom. This appears to be associated with a sinking mass of dying plankton. Verjbinskaya's (1932) results show that in the Barents Sea a large production of nitrite similarly accompanies plankton production, reaching high values at depths of 50–100 metres, especially at boundaries such as the bottom of the Arctic water. In winter, when there is little plankton and much mixing, no nitrite is present.

Cooper (1933*a*) did not find a similar depth distribution of nitrite in the English Channel, perhaps owing to the fact that there is no appreciable discontinuity layer at the time of the spring plankton maximum. In a later paper, however, he (Cooper, 1933*b*) gives figures for station E 1 in August, 1932, when the water was very stable, and there we do find a small peak in the nitrite profile at the bottom of the thermocline.

Deacon (1933) finds in the Antarctic water up to 8 mg.  $\text{NO}_2\text{-N/m}^3$  in the surface 100 metres, but never any below the discontinuity. In the sub-antarctic zone he finds up to 30 mg.  $\text{N/m}^3$  just below the discontinuity layer which marks the bottom of the tropical water.

As far as it goes, previously recorded data seem to show a similar distribution to that found in the Indian Ocean region. Excepting Orr's (1926) paper, the phenomenon seems to have attracted little attention, and most authors have either made no comment, or passed it over with a brief remark to the effect that nitrite is a stage in the nitrification of organic residues—a process about which little is known. Unfortunately in spite of a good deal of scattered information about bacteria, we still do not know very much about the part they play or about the nitrification process,\* but in view of the considerable amount of data accumulated on the John Murray Expedition, we are in a position to generalize to some extent on the distribution of nitrite, and its relation to that of the phytoplankton.

From the presence of relatively large quantities of nitrite just below the zone of maximum productivity, at levels where we should expect to find dead and dying phytoplankton sinking towards the depths, it seems probable that the two are connected. This is supported by the fact that these zones of high nitrite are especially prominent where a rapid change in the density of the water tends to hold up the sinking particles,† and further by the cultural experiments already described (*cf.* also Orr, 1926, where he mentions that nitrite increased in cultures, continuing to increase after the diatoms had ceased to do so). The quantity of nitrite found depends on the relative rates of formation and destruction, and does not bear any direct quantitative relation to the amount of plankton material. However, since its formation must depend on the supply of organic matter,‡ it is a reasonable inference that a high nitrite concentration indicates the production of rich supplies of organic material by the plankton, while a low nitrite may have several explanations. In conjunction with abundant plankton it indicates that

\* See below, p. 62.

† That a discontinuity does tend to cause an accumulation of particulate matter is clearly shown by measurements of the penetration of light, *e. g.* Oster and Clarke (1934), Uterback (1933), and Pettersson (1935).

‡ See below, p. 65.



production has recently begun, so that there is as yet no great amount of organic matter free in the water—the initial phases of an outburst; such conditions will usually be accompanied by relatively high concentrations of nitrate and phosphate in the illuminated layers. This stage is a very short one, and a certain amount of nitrite can be formed before all the nitrate and phosphate are exhausted. Where plankton is sparse, this is in itself an explanation, and the absence of nitrite indicates that it has been sparse for some time. Such conditions are most commonly found in temperate and polar seas in winter, when lack of light limits plankton production. Where the discontinuity layer is absent, or near the surface, so that the productive zone extends well below it, there will be no tendency for an accumulation of organisms at any one level, and there may be no level at which the production of nitrite greatly exceeds its destruction, and therefore no level at which any large amount is found. Under these conditions the absence of a marked nitrite peak does not necessarily indicate a small plankton production.

## (ii) THE DISTRIBUTION OF NITROGEN COMPOUNDS IN THE NORTHERN INDIAN OCEAN.

The John Murray Expedition was at work for nine months from September, 1933, to May, 1934. The area investigated, and the positions of the stations at which nitrate, nitrite or phytoplankton determinations were made in addition to the routine observations of temperature, salinity and oxygen are shown on the chart by their serial numbers in the expedition's station list.

The results of the analyses are shown graphically in Text-figs. 2 to 13, which represent profiles of the upper 300 metres of the water column, concentration being plotted as abscissa against depth as ordinate. The full data are also given in the tables in the appendix to Vol. II of these reports. Concentrations of nitrate and nitrite are given in milligrams of nitrogen per cubic metre of water (mg. N/m<sup>3</sup>); the oxygen content is given as the percentage of the saturation value for water of similar salinity and temperature; the pH values given have been corrected for salinity and temperature, and show the pH of the water *in situ*. In the stability diagrams the width of the figure is proportional to the average rate of change of density ( $\sigma_t$  units per 10 m. depth) between any two sampled depths—negative values are shown white. It should be noted that in these calculations the effect of pressure has been neglected. This is not strictly permissible, and does not give the true value for the stability, but at the small depths here studied the results are quite sufficiently accurate for the purposes of this discussion. The phytoplankton is reported in arbitrary units of plant pigment per cubic metre of water; in order that the figure might be comparable with his for the English Channel, the unit devised by Harvey (1934*a*) was used. Each rectangle in the diagrams shows on the horizontal scale the average plankton content, and on the vertical scale the portion of the water column fished by the net on each haul.

The Secchi disc readings are shown by a short horizontal line near the right-hand edge of the figure, the depth being given below it thus:  $\overline{SD} = 22.5$  m. The horizontal broken line across the figure shows the compensation depth calculated as  $2.5 \times$  the SD reading (see p. 37).

In the discussion of the results which follows, the stations are considered in groups, each of which represents a section across a body of water. In some cases diagrams to

show the distribution of nitrate in the section are given. The movements of the water have been deduced partly from these diagrams. These movements have been confirmed and amplified by information kindly supplied by Dr. E. F. Thompson, and derived by

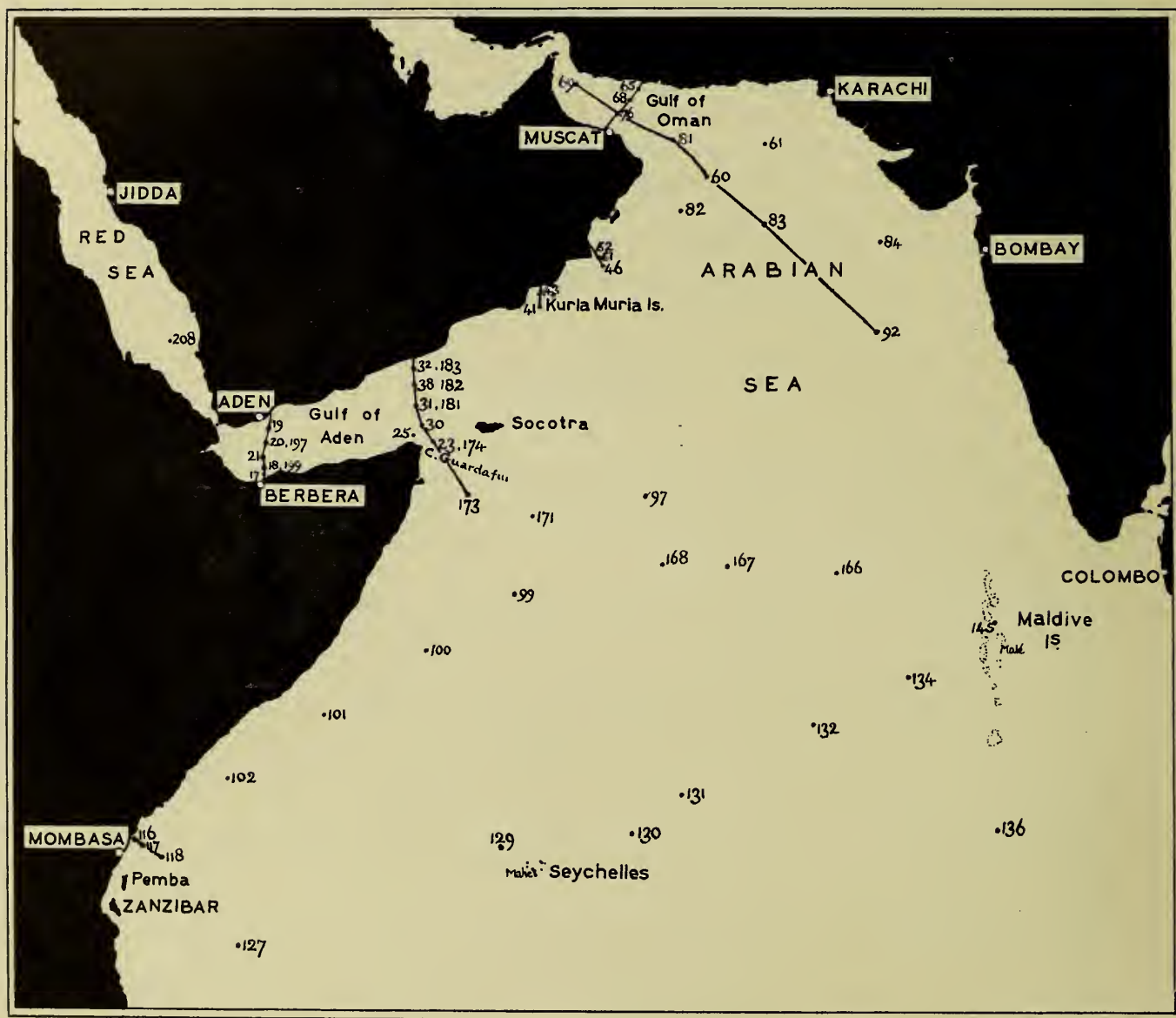


CHART.—The area investigated and stations where determinations were made.

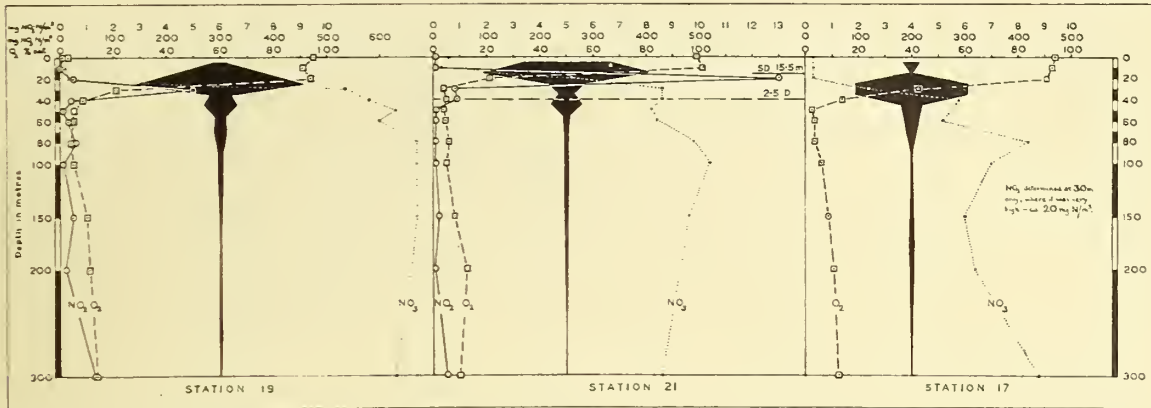
him from his work on the salinity and temperature data; this applies especially to the questions of the origin of the various masses of water.

#### (1) *The Gulf of Aden.*

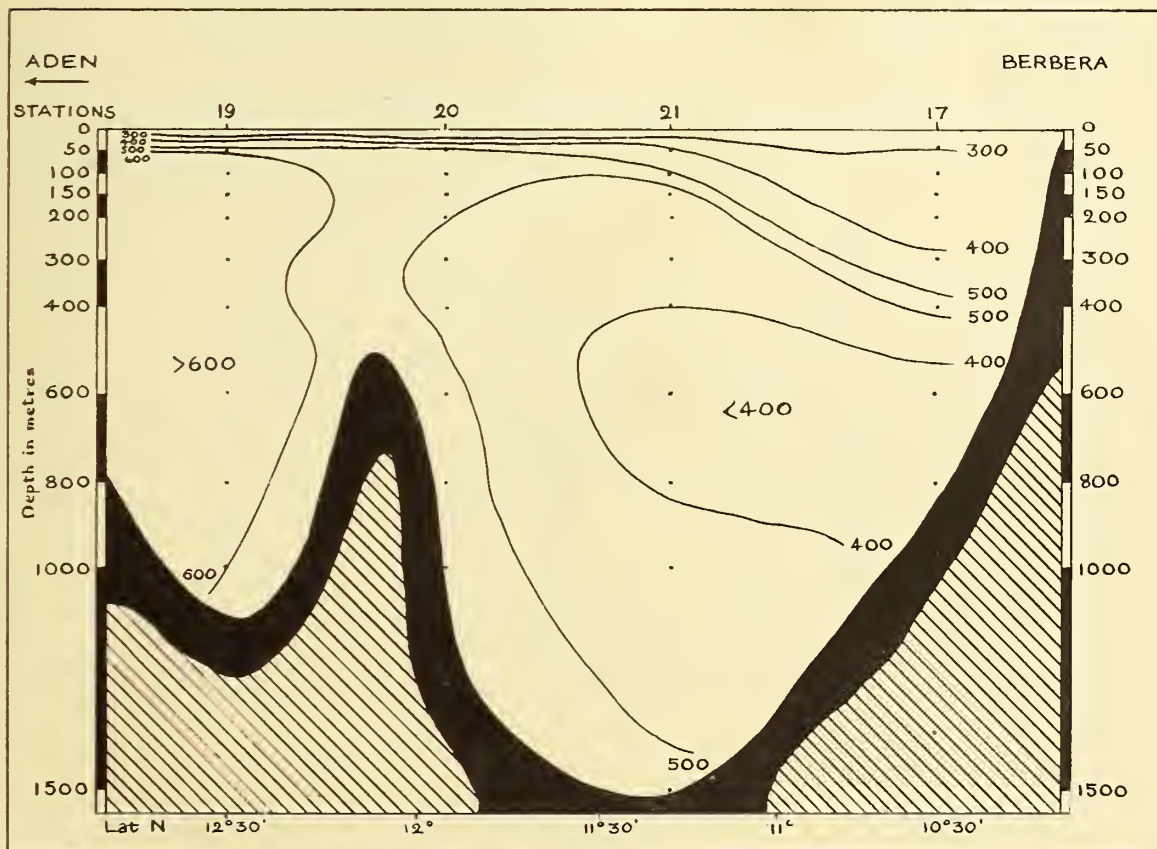
*Aden Section.* Stations 17–21. September, 1933. (Text-figs. 2 and 3.)

The distribution throughout this section conforms closely to a single type dominated by the presence of a very sharp discontinuity layer (see Text-fig. 2). In the northern

half of the section this lay between 20 and 30 metres ; at Station 21 upwelling of water from below had pushed it up into the 10-20 metre layer. There was a sharp division at



TEXT-FIG. 2.



TEXT-FIG. 3.

this level between the warm, saline, surface water, which was depleted of nitrate and approached saturation with oxygen, and a lower layer of cooler, less saline water with a



very low oxygen content. Nitrite reached high values just below this density boundary, owing to the decay of sinking plankton held up at that level.

The deeper layers show a more or less uniformly high nitrate concentration, tending to be higher in the northern half of the section. This is readily explained by the section diagram (Text-fig. 3), which shows that there was a mass of water rich in nitrate (more than 500 mg. N/m<sup>3</sup>) hugging the northern shore. This water comes originally from the depths of the southern part of the Indian Ocean. It is carried north in a current which sweeps along the coast of Africa, rising nearer the surface on its way, until finally it strikes the Arabian coast. It then divides, and part moves west along the northern shore of the Gulf of Aden. On the south side of the Gulf was a mass of water lying between 400 and 1000 metres, which contained less than 450 mg. NO<sub>3</sub>-N/m<sup>3</sup>, and had a very high salinity and temperature. This is mid- and bottom-water from the Red Sea moving east down the Gulf towards the open ocean.

Near the southern shore the downward trend of the iso-nitrate lines shows that the wind had piled up the water of the top 200 metres against the coast, causing a downward movement of surface water.

*Gardafui Section.* Stations 23-38. October, 1933. (Text-figs. 4 and 5.)

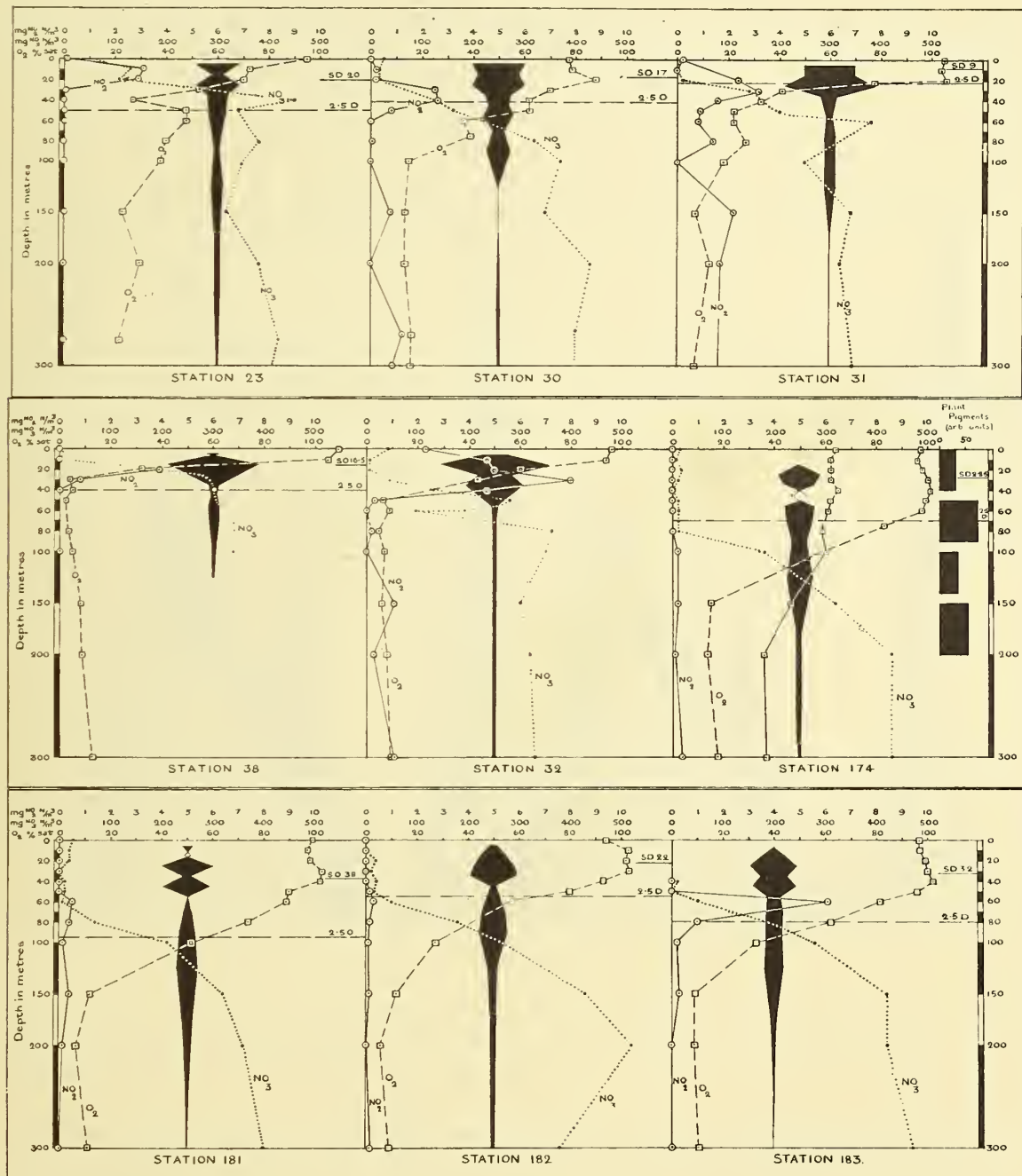
The main water masses that we saw in the more westerly section in the longitude of Aden were here in somewhat different positions (see Text-fig. 5). The oceanic water containing more than 450 mg. N/m<sup>3</sup> was here found entering the Gulf at the bottom near the south side, where it was pushed up towards the surface by the ridge which runs between Cape Gardafui and the Island of Socotra. The Red Sea water had mostly moved over to the northern shore, where it forms a vortex in the middle depths. A small proportion moves further south and out into the open ocean, but as it also moves to a higher level among water of a similar nitrate concentration, it does not appear on the nitrate diagram. The result of the upward movement over the Socotra-Gardafui ridge is to bunch together the layers below the surface, so that the water found at Station 23 at about 100 metres was similar to that found about the 300-metre level at the north end of the section. The effects of this turbulence are clearly seen at Station 23 (Text-fig. 4), where the stability was comparatively low, and nitrate was high and oxygen low up to 10 metres below the surface.

As we go north along the section away from this area of turbulence, the stability increases, and we pass gradually into conditions more like those at the western end of the Gulf. At Station 38 we again find the sub-surface layer bunched together somewhat, but there was not the same degree of turbulence as at Station 23. Nitrite again showed peaks in the boundary layers.

*Gardafui Section.* Stations 174-183. May, 1934. (Text-figs. 4 and 5.)

The deep ocean water which, in October, was moving into the Gulf on the south side of the section between 600 m. and the bottom, now filled the entire bottom of the Gulf, as it poured over the Socotra-Gardafui ridge. The outgoing water from the Red Sea had been pushed upwards, and now occupied a central position between 300 and 600 metres (see Text-fig. 5).

Along the Arabian coast the change from the strong winds of the SW monsoon season to the gentle off-shore winds of the NE monsoon had produced considerable

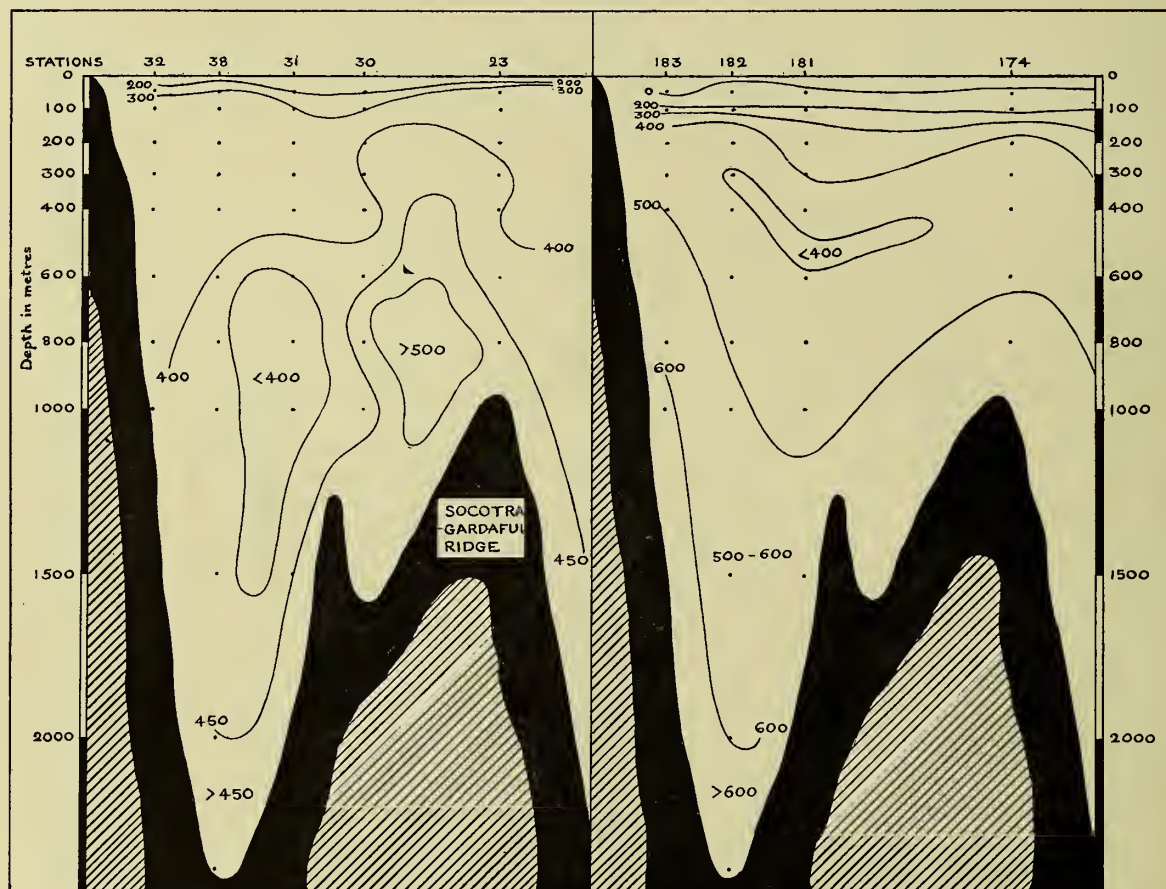


TEXT-FIG. 4.

changes. There was no longer water piled up against the coast and so forced to sink, as at Station 32. Instead there was at Station 183 a tendency for the deeper water to approach the surface, and this tendency was even more marked at Station 182. Water

was also being pushed up at Station 174, as the deep water poured over the Socotra-Gardafui ridge.

The calm weather had allowed a much thicker warmed layer to develop at the surface, although with increasing thickness of this layer the temperature gradient had become less steep, and the stability less than it was in October (see Text-fig. 4). The higher transparency indicates that the plankton had either diminished, or sunk to lower levels, and probably the latter is principally the case. The oxygen curves all show peaks at about



TEXT-FIG. 5.

30–40 metres, which was therefore the zone of maximum production. This is borne out by the plankton data of Station 174, where the richest haul was obtained between 50 and 90 m.\*

Nitrite curves show small peaks just below the limit of the layer depleted of nitrate. Where this falls at a boundary, the peak is more pronounced (*e. g.* Station 183).

In October the moderate oxygen concentrations in the surface layers, the high nitrite figures, and the depletion of nitrate in the upper 20 metres, indicate that phytoplankton had already passed its zenith, and was limited by lack of nutrient salts in the productive zone. Although the very stable conditions were partly due to the different origins of the water, they were probably of comparatively short standing, and were changing rapidly

\* This statement appears paradoxical, but see p. 38.



as the result of the recent change from rough to calm weather. The depth of the layer depleted of nitrate falls in most of the stations far short of the calculated compensation point, although the transparency was low. This is probably because the sharp discontinuity was holding up the growing organisms, and preventing their colonizing the unexhausted water below, so that conditions were not in a static equilibrium. It is also possible that any which did penetrate would develop much more slowly in the cooler water below.\*

Unfortunately no quantitative plankton observations were made, but the area was observed to be rich in the larger zooplankton. The bulk of the surface plankton caught in the high-speed tow-net was species of *Ceratium* with a few Copepods and *Sagitta*. This is the type of plankton to be expected in warm water poor in nutrients, and Col. Sewell suggests that it was probably brought in by the surface East African coastal current.

Since there are no rivers in the area, and almost no rainfall, the low transparency cannot be attributed to material washed out from the surface of the land. Further, since the water is mostly deep, and the shores are steep-to and rocky, it is not easy to see how much detritus can have been stirred up off the bottom, even by the storms of the SW monsoon. The suspended matter in the sub-surface layers must, then, have been mainly zooplankton organisms—a not improbable conclusion, since the area, as one of considerable vertical mixing, would be expected to be a productive one.

In May conditions were more nearly in equilibrium. Warming by the sun had pushed the thermocline deeper, and the plankton penetrating through the less sharp discontinuity had carried the depletion of nitrate almost to the limit set by illumination.

Owing to supplies of nutrients brought up by turbulence, from which the plankton was no longer cut off by a steep and shallow thermocline, there was active production in progress, maintaining high oxygen concentrations. The low nitrite figures are a little surprising, since in view of the extensive depletion of nitrate, production cannot be supposed to have begun very recently.† The reason is perhaps the absence of any marked discontinuity at the lower limit of the productive zone, so that there might be no tendency for an accumulation at any one level. It must also be remembered that the layers of high nitrite are often very thin and sharply defined. It is therefore possible that, especially in the calm conditions prevailing with little mixing by wind, observations 10 metres apart might miss the maximum value, so that the absence of a peak in the recorded curves does not necessarily show its absence in fact. Since conditions in the surface layers were very uniform throughout the section as a whole, it may be that whereas in October the depths sampled tended to strike the peak value at all stations, in May they similarly tended to miss it at all stations.

## (2) *The Arabian Coast.*

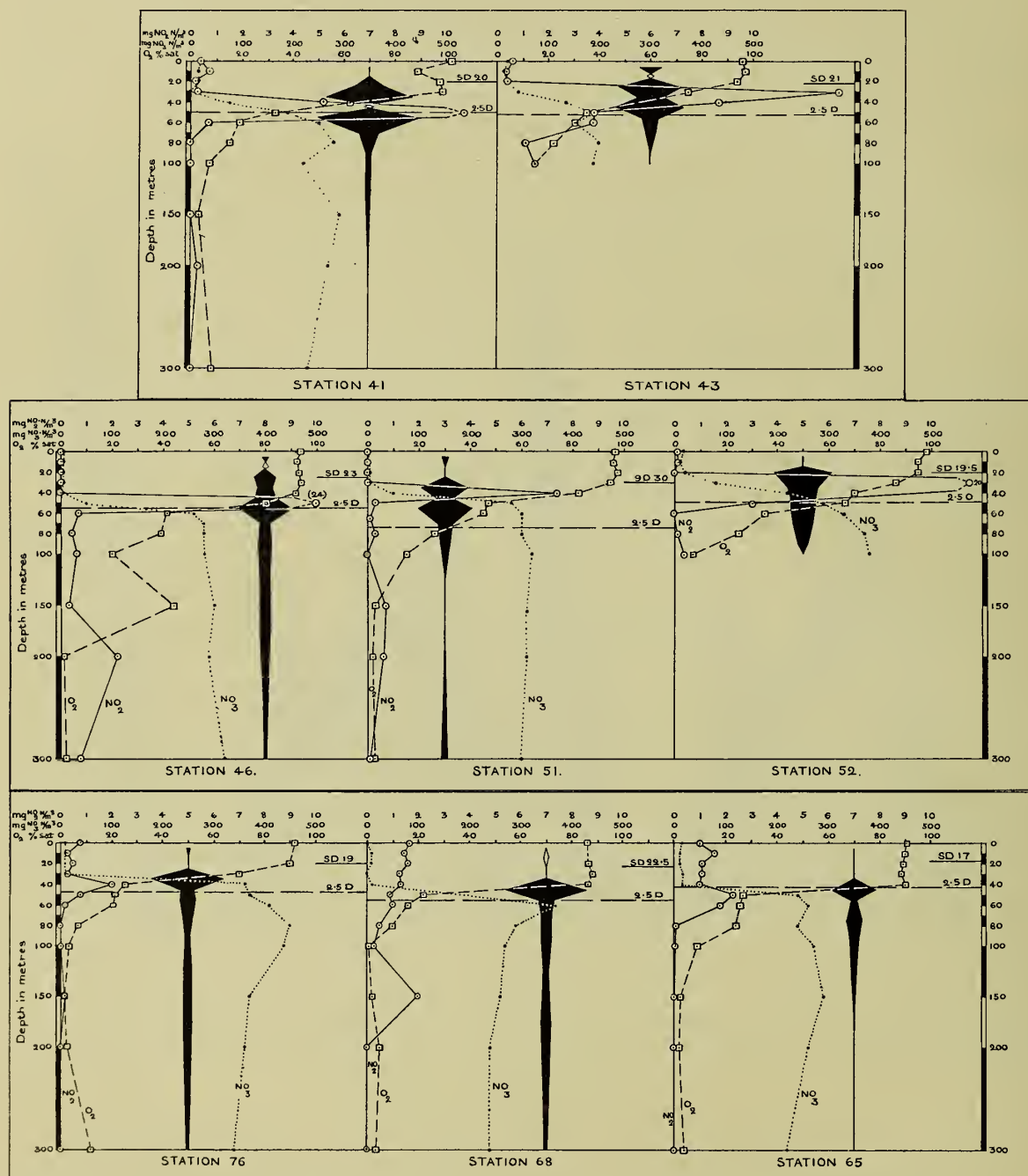
*Arabian Coast Sections.* Stations 41–52. October, 1933. (Text-figs. 6 and 7.)

Conditions here appear to have been in the transition phase between the two monsoons. The upwelling along the coast, which occurs in the SW monsoon season, was falling off,

\* For similar limitation of the productive layer by the thermocline, see Seiwel (1935), who attributes the effect to the influence of temperature on the organisms.

† The May outburst recorded by Hornell and Ramaswami Nayudu (1923) off the Malabar coast is definitely correlated with the rain brought by the SW monsoon or the unsettled weather which precedes it. Similar conditions do not obtain here, where the monsoon brings little or no rain, and in any case had not yet broken at the time under discussion.

and only appears in the water below 100 metres and some way off shore. There was, however, a slight upward movement in the surface layers at Station 52, probably owing to the NW wind blowing at the time of observation. As a result of this movement it



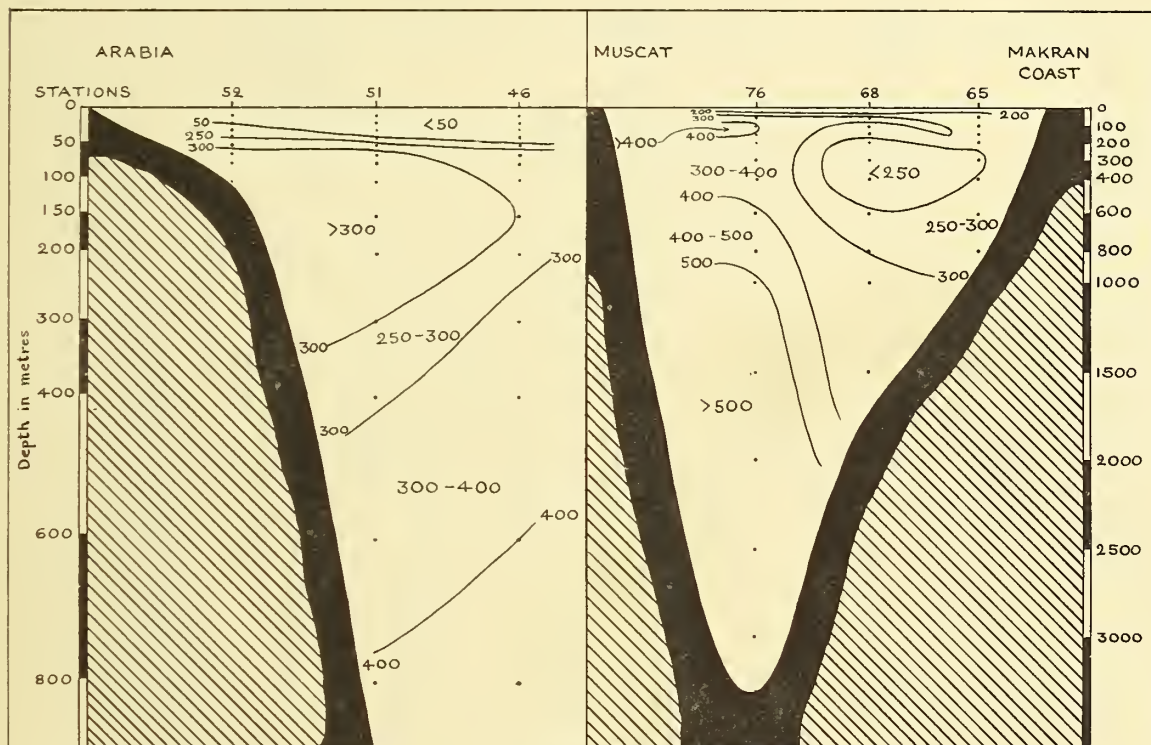
TEXT-FIG. 6.

was only the well-mixed surface layer which was depleted of nutrient salts at the inshore stations, while in the more stable conditions further out at Station 46 depletion had proceeded down to 40 metres.

The oxygen, nitrite and transparency figures suggest that a period of considerable



plankton production was just coming to an end, and there were great quantities dying off in the discontinuity layer. This is confirmed by the abundant zooplankton, especially salps, which was observed here. As far as plankton is concerned, the area resembles the Gulf of Aden. The supplies of nutrients brought up from below by the SW monsoon support a large but short-lived outburst of phytoplankton, which develops in the increasingly stable conditions following the change of wind, and subsequently provides food for a rich zooplankton.



TEXT-FIG. 7.

### (3) *The Gulf of Oman.*

*Muscat Section.* Stations 65, 68, 76. November, 1933. (Text-figs. 6 and 7.)

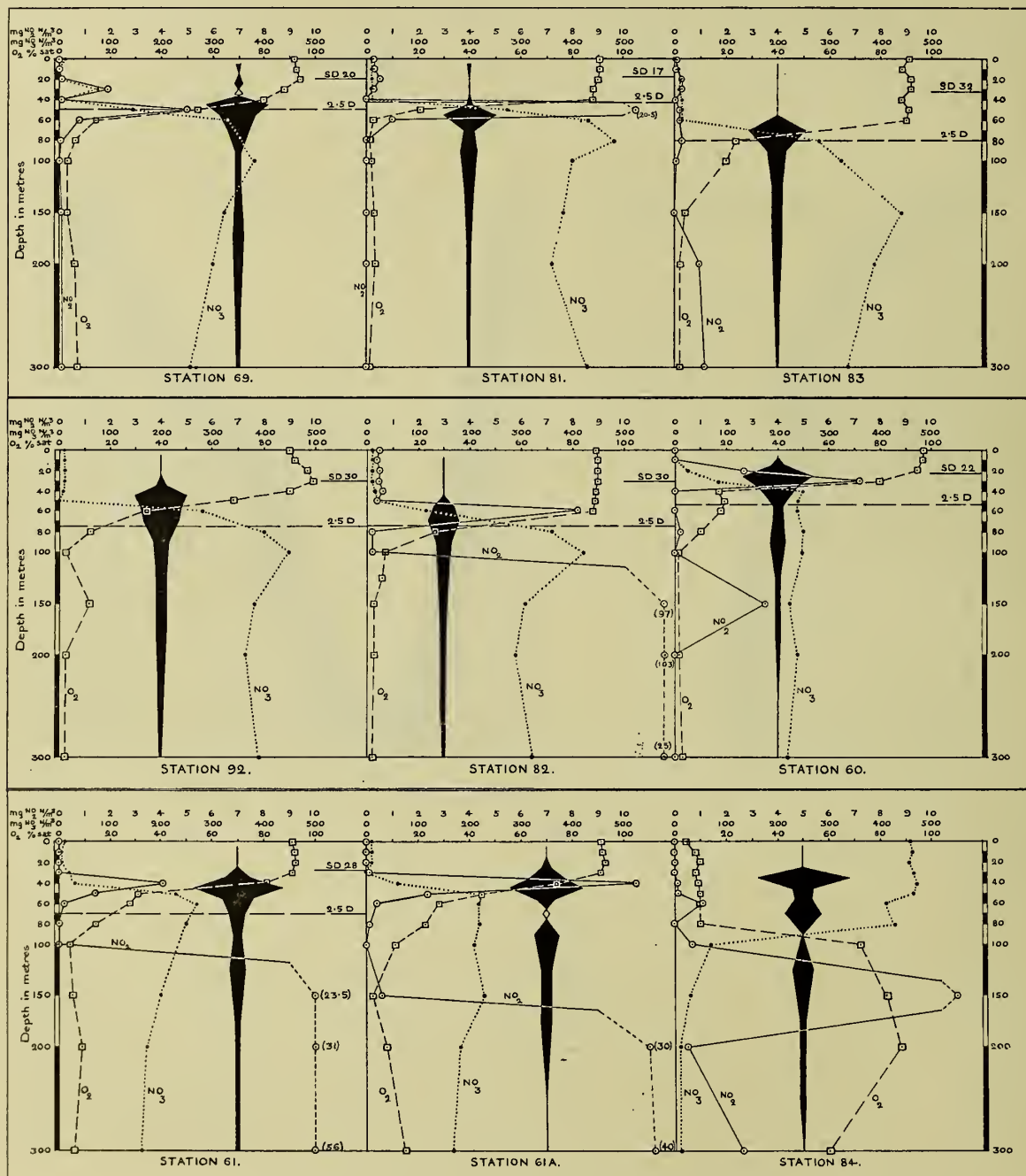
Lying between 200 and 600 metres in the north-eastern half of the section (Text-fig. 7) is a body of water of relatively high salinity containing less than 300 mg.  $\text{NO}_3\text{-N/m}^3$ ; this is water moving north towards the Persian Gulf from the broad extension of the continental shelf off Bombay. On the Arabian side at about 150 metres depth is a tongue of water of lower salinity and rich in nitrate coming out of the Persian Gulf. The deep water below 1000 metres has a much lower salinity and higher nitrate content (more than 500 mg.  $\text{N/m}^3$ ), and is deep ocean water from the Arabian Sea.

Throughout the section there is a well-mixed surface layer from 30 to 40 metres thick, which is almost completely depleted of nutrient salts. The comparatively low oxygen figures indicate a sparse plankton owing to lack of nutrient salts. Nitrite shows some evidence of dying plankton in the discontinuity zone, and rather high values throughout the surface layer, probably owing to mixing by the wind.



*Gulf of Oman Section. Stations 69-92. November to December, 1933.*  
(Text-figs. 8 and 9.)

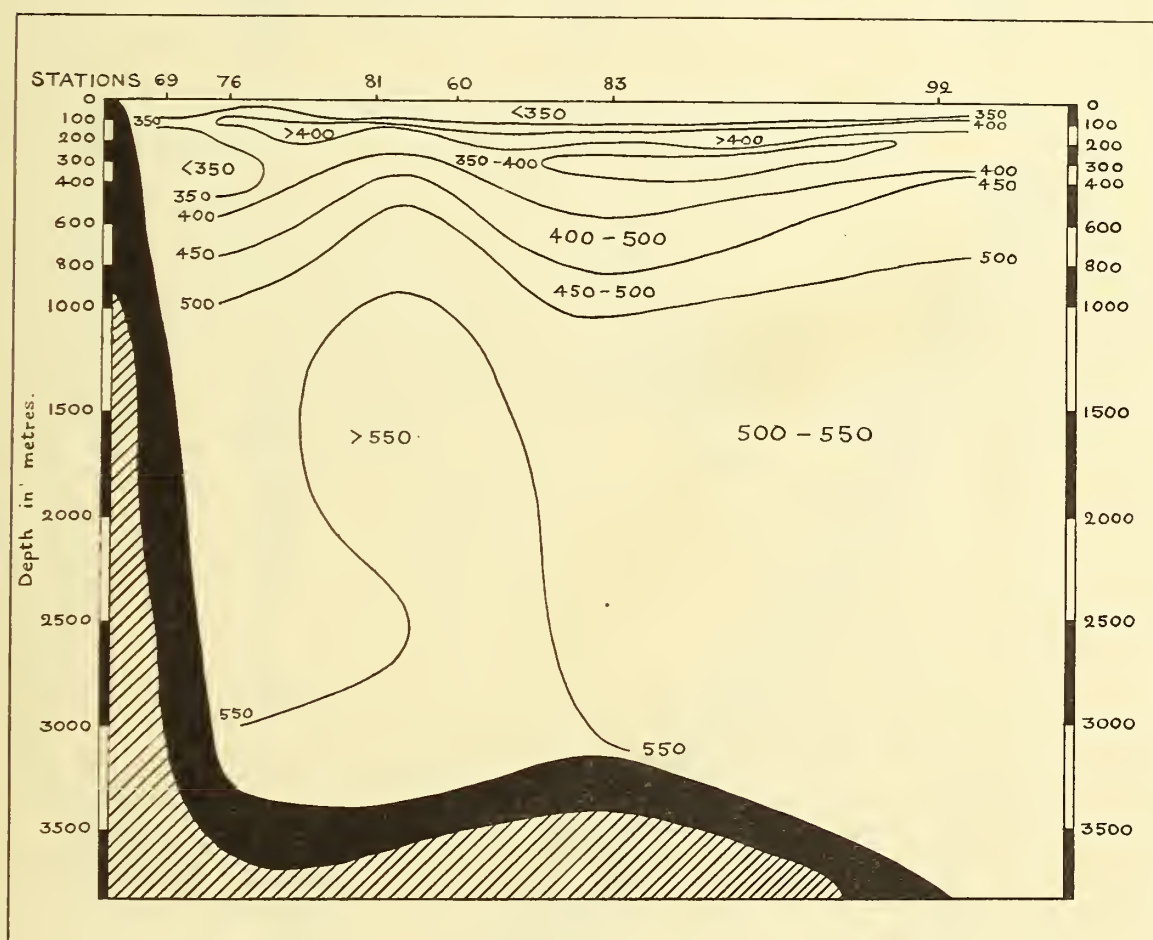
The longitudinal section through the Gulf shows the Persian Gulf water, containing more than 400 mg.  $\text{NO}_3\text{-N}/\text{m}^3$ , moving south at depths between 100 and 200 metres, and



TEXT-FIG. 8.

hugging the Arabian shore. Below it the nitrate-poor water from the Bombay region appears at some stations, but since it tends to keep to the Persian side, it does not appear at all of them (see Text-fig. 9).

The area appears to be one of comparatively scanty plankton production. Although more or less landlocked it receives no considerable supplies of nutrient salts from land, owing to the extremely small rainfall. The currents are of moderate velocity, but apparently produce little turbulence, so that although the stability is not very high, it is sufficient to prevent any considerable enrichment of the productive zone from below. The transparency was also low, probably owing to detritus carried out from the shallow waters of the Persian Gulf. At most stations nitrate was depleted almost down to the limit

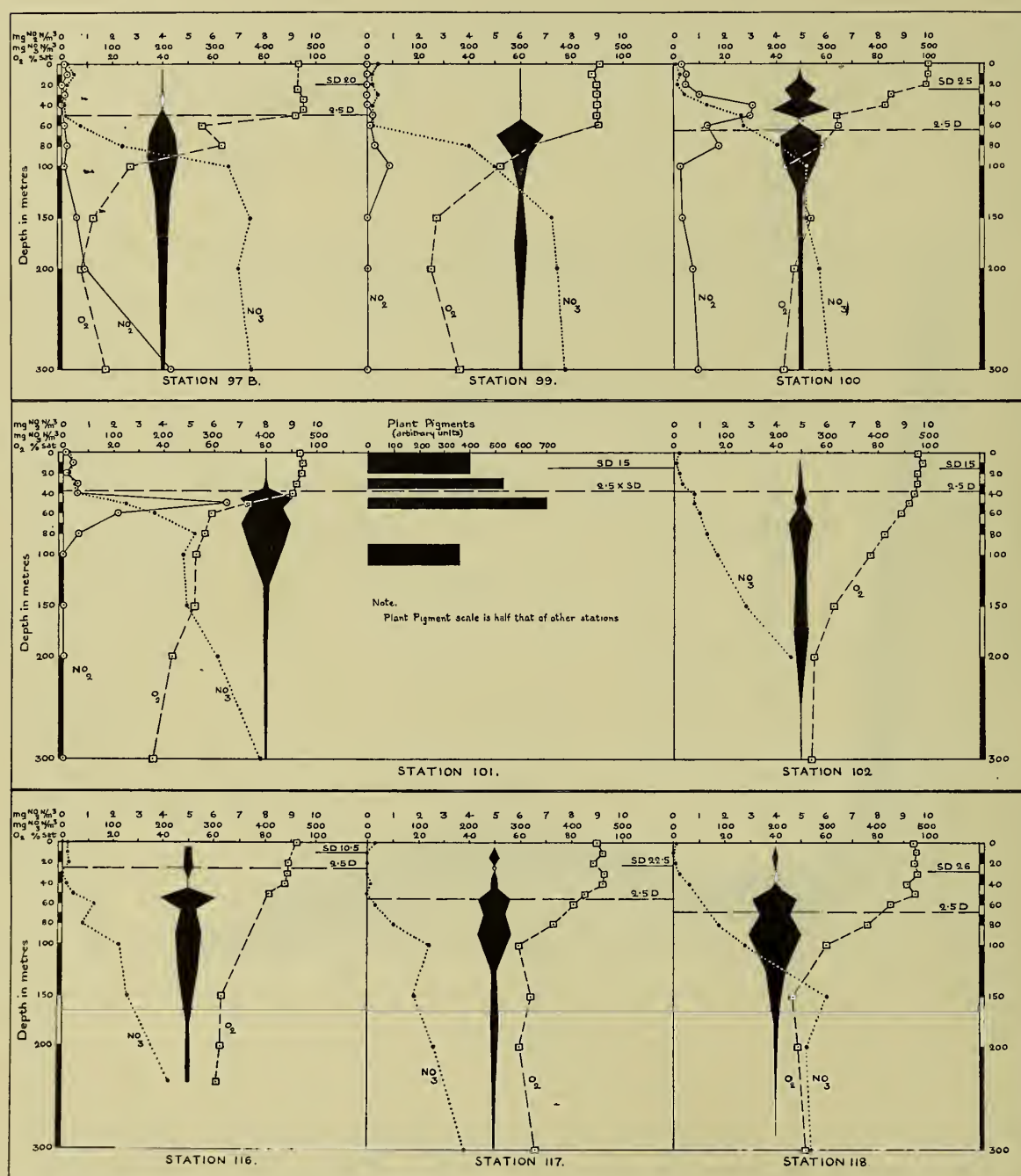


TEXT-FIG. 9.

set by illumination, so that its lack was certainly limiting production. Neither oxygen nor nitrite figures (except Station 81) indicate any recent production on a large scale; if there is an outburst after the break-up of the SW monsoon, as we have seen in neighbouring areas, it must have been already long past by the time the expedition visited this area.

The phenomenally high nitrite concentrations recorded between 150 and 600 metres at Stations 61, 82, 84 and 92, and at 1000 metres at Station 83 (see tables in appendix to Vol. II), call for some comment, since some of these figures are far higher than anything previously recorded. Atkins (1930) reported finding 38.9 mg.  $\text{NO}_2\text{-N/m}^3$  below the

thermocline in August off Plymouth, but the concentration at 200 metres at Station 82 (103 mg. N/m<sup>3</sup>) was nearly three times this value. While no explanation can at present



TEXT-FIG. 10.

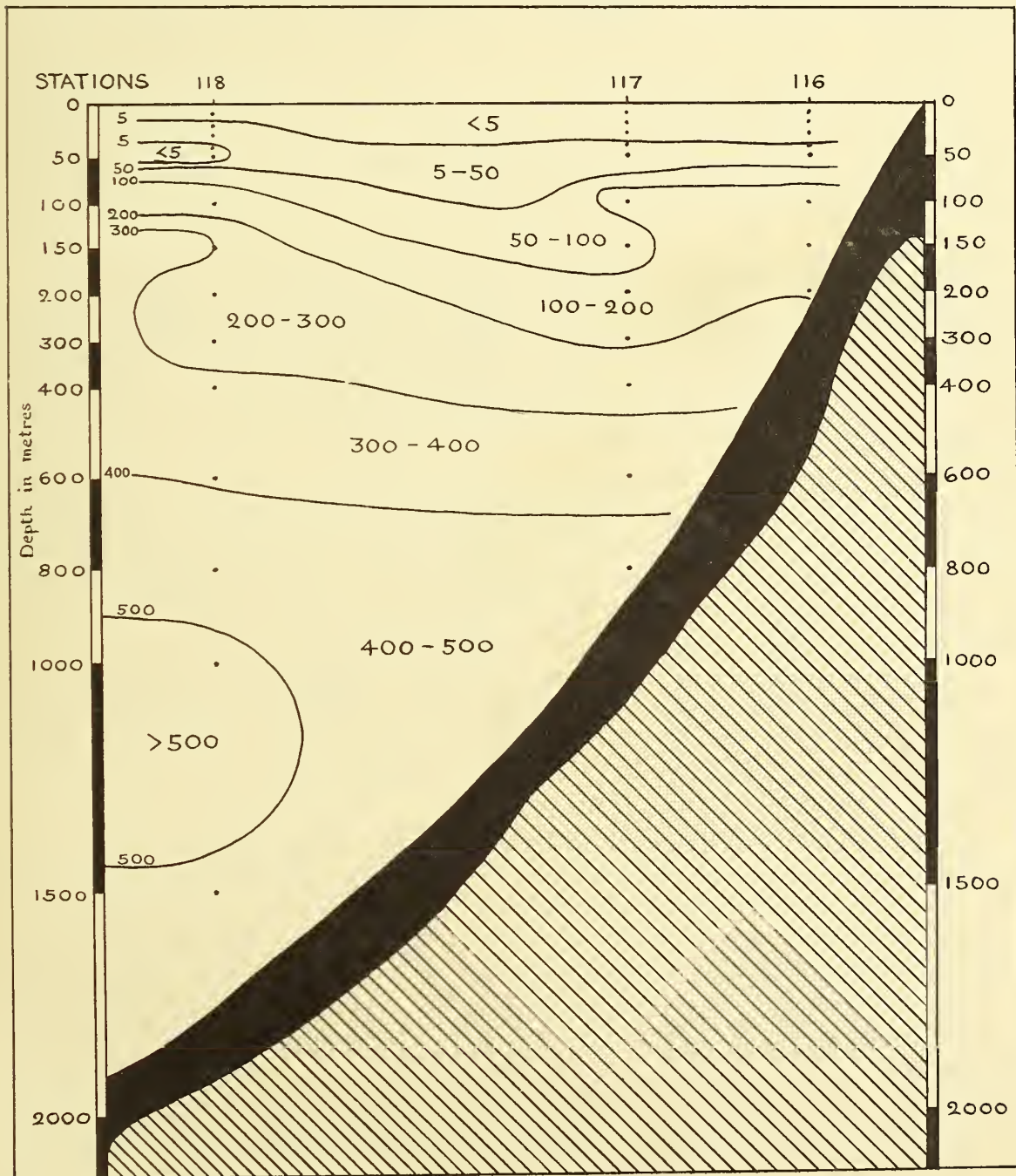
be given, the fact that these stations lie in the neighbourhood of the "dead areas" described elsewhere in these reports by Col. Sewell (1935) is suggestive, but the connection cannot be regarded as established.



(4) *The Arabian Sea.**Northern Section.* Stations 92-118. December to January, 1933-4.

(Text-figs. 10 and 11.)

From Bombay as far as Station 100 conditions were fairly uniform. The surface layer was well mixed as far down as 50 or 60 metres, and almost completely depleted of nutrient salts. There does not seem to have been recent plankton production on any scale, and the area is probably always a poor one owing to lack of available nutrients.



TEXT-FIG. 11.

At Station 100 we come into the sphere of the extremely rapid African coastal current, and enter the area of the richest plankton encountered by the expedition. During the SW monsoon season the northerly current along the African coast tends to move in a more easterly direction under the influence of the wind, and upwelling of deeper water results along the coast (see Matthews, 1926). The relics of this movement can be seen in the profiles at Stations 100 and 101 (see Text-fig. 10), although at the time when the Expedition visited the area the NE Monsoon was well established, and its influence is clearly seen in the stations closer to the shore. There the downward movement of water piled up against the coast is well shown by the small nitrate and oxygen gradients at Stations 102 and 116. The same tendency appears in a rather smaller degree at Stations 117 and 118 (see Text-figs. 10 and 11).

Unfortunately nitrite analyses could not be carried out for several of these stations, but where figures are available they resemble those of the Gardafui section in October, which, as we have already seen, was also a highly productive area. Again we find high values associated with a rapid change of density.

*Southern Section.* Stations 127-145. February to March, 1934. (Text-fig. 12.)

As in the northern section, the surface 40 or 50 metres had a comparatively low stability. Mixing by wind was more marked at the western side of the basin, where the NE monsoon is stronger, and has a greater fetch. However, as the compensation level lay at about 60 to 80 metres, well below the limit of such mixing, it caused no renewal of the supplies of nutrient salts.

The open ocean stations appear to show stages following the end of a small phytoplankton outburst, the plankton having mostly sunk below the compensation point, and reached various stages of death and decay. On the whole the process is more advanced as we go east. Since this is the direction in which the expedition traversed the section, this may be due simply to the fact that the eastern stations were worked later than the western ones.

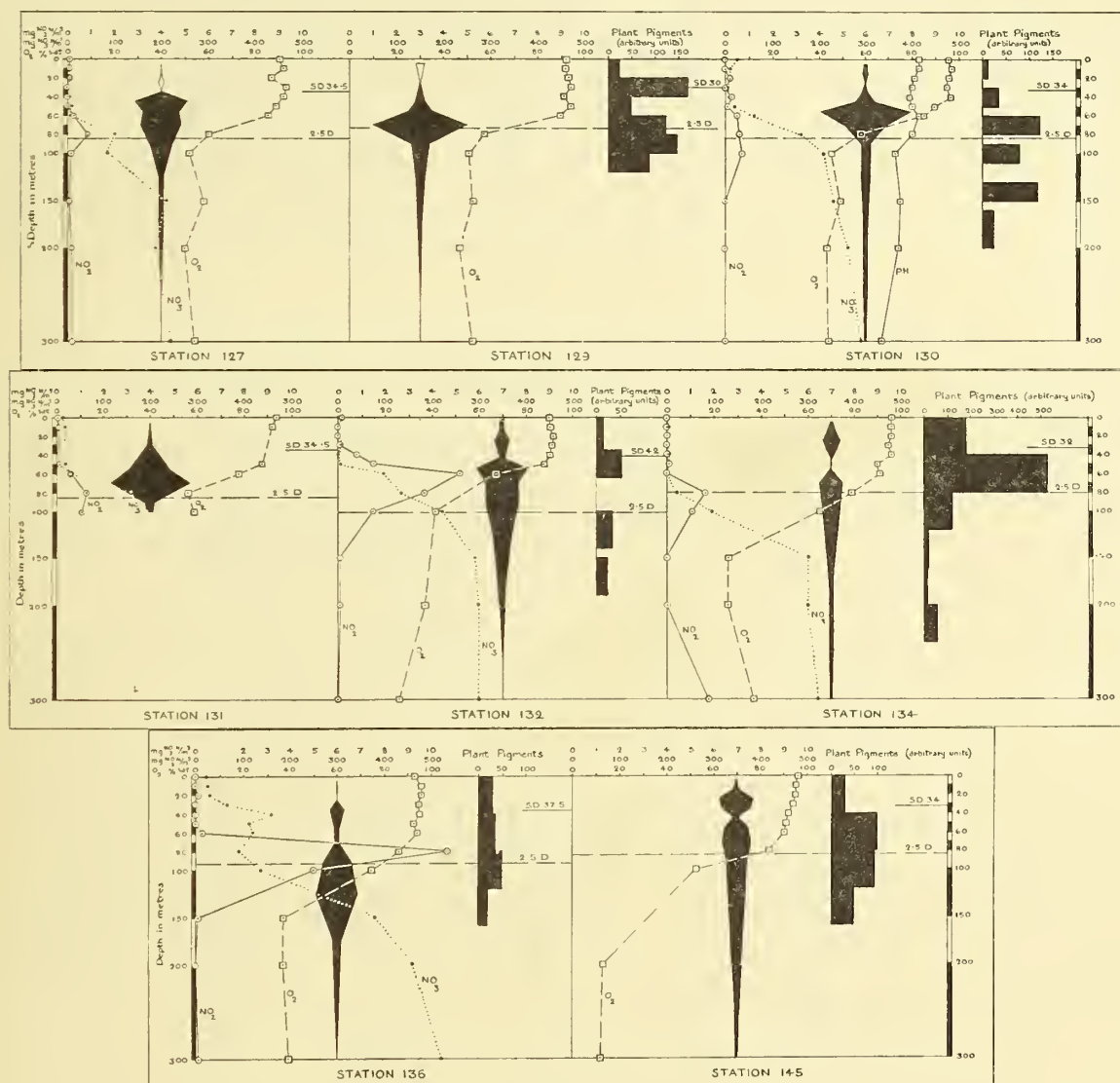
This outburst is probably conditioned by the return of calm weather, and the consequent greater stability in the surface layers, at the end of the SW monsoon season. With the advent of the NE monsoon mixing will increase again, but by this time the plankton is limited by exhaustion of its supplies of nutrients, and will be little affected. This was the condition at the time of observation.

Stations 129 and 134\* both show higher plankton figures, especially near the surface (see Text-fig. 12). In the case of Station 129 this is due to upwelling under the lee of the Seychelles bank, and the upward movement is shown by the lower temperatures as compared with corresponding depths at Station 127. Station 134 might possibly be influenced similarly by the Maldivé ridge, but the station is some way from the ridge, and the temperatures show no evidence of upwelling. On the other hand the salinity at the surface was distinctly lower than at Station 132. This indicates an influx of water from elsewhere, and Matthews (1926) has shown that this low salinity water is brought by the NE monsoon from the Bay of Bengal, Andaman Sea and the Malay region. Since enormous quantities of nitrate are brought down into the Bay of Bengal by the Ganges, it may well be that the water of this area is characterized by a relatively high nitrate content,

\* Colonel Sewell informs me that this station was also very rich in small Copepods.



but unfortunately there are no analyses available to establish the point. The oxygen figures for this station (134) show clearly by the absence of any corresponding peak at that level that the phytoplankton found abundantly in the 40–80 metre layer did not originate there, but was sinking from above. Enrichment of the surface layers only will



TEXT-FIG. 12.

therefore explain the distribution found, and we are observing the same “aftermath” position that we have already discussed in the other stations.

If the magnitude of the nitrite peak is a true indication of the amount of planktonic decay which is going on or has recently occurred, Station 136, which was worked nearly four weeks later, shows a still more advanced stage of this process. The incomplete utilization of nitrate here is rather surprising. The position of the station on the ridge connecting the Maldives and the Chagos Archipelago suggests that there might be upwelling here too, but the relatively high stability between 100 and 150 metres makes this appear



unlikely—a conclusion which is borne out by the fact that the temperatures were slightly higher than those at corresponding depths at Stations 132 and 134. Possibly there had been regeneration of nitrate in the surface layers, or there may have been renewal by horizontal movements from the Bay of Bengal area, though the latter is not supported by the salinity. In any case unless some other factor, such as lack of phosphate, was limiting the plankton (in which case we need not postulate any influx of nitrate), any such renewal must have taken place very shortly before the time of investigation, since there was as yet no sign of a fresh plankton outburst.

Station 145 in the shallow water (494 m.) in Kardiva Channel shows the same type of conditioning as the other stations in the area. Unfortunately no analyses of the nitrogen compounds were made, but the absence of a peak in the oxygen curve indicates that the relatively large amount of phytoplankton had passed its period of maximum productivity.

*Central Section.* Stations 166–173. April, 1934. (Text-fig. 13.)

Excepting No. 173, the stations in this section show a large degree of similarity, the stability tending to decrease as we go westwards. The oxygen curves all show maxima well below the surface, and corresponding with plankton maxima where the figures are available. This indicates an active production of plankton in the layers between 20 and 60 metres, where the layer of optimum illumination probably lay, the light being almost certainly too intense near the surface. The transparency was high, and there was a correspondingly thick layer rich in oxygen.

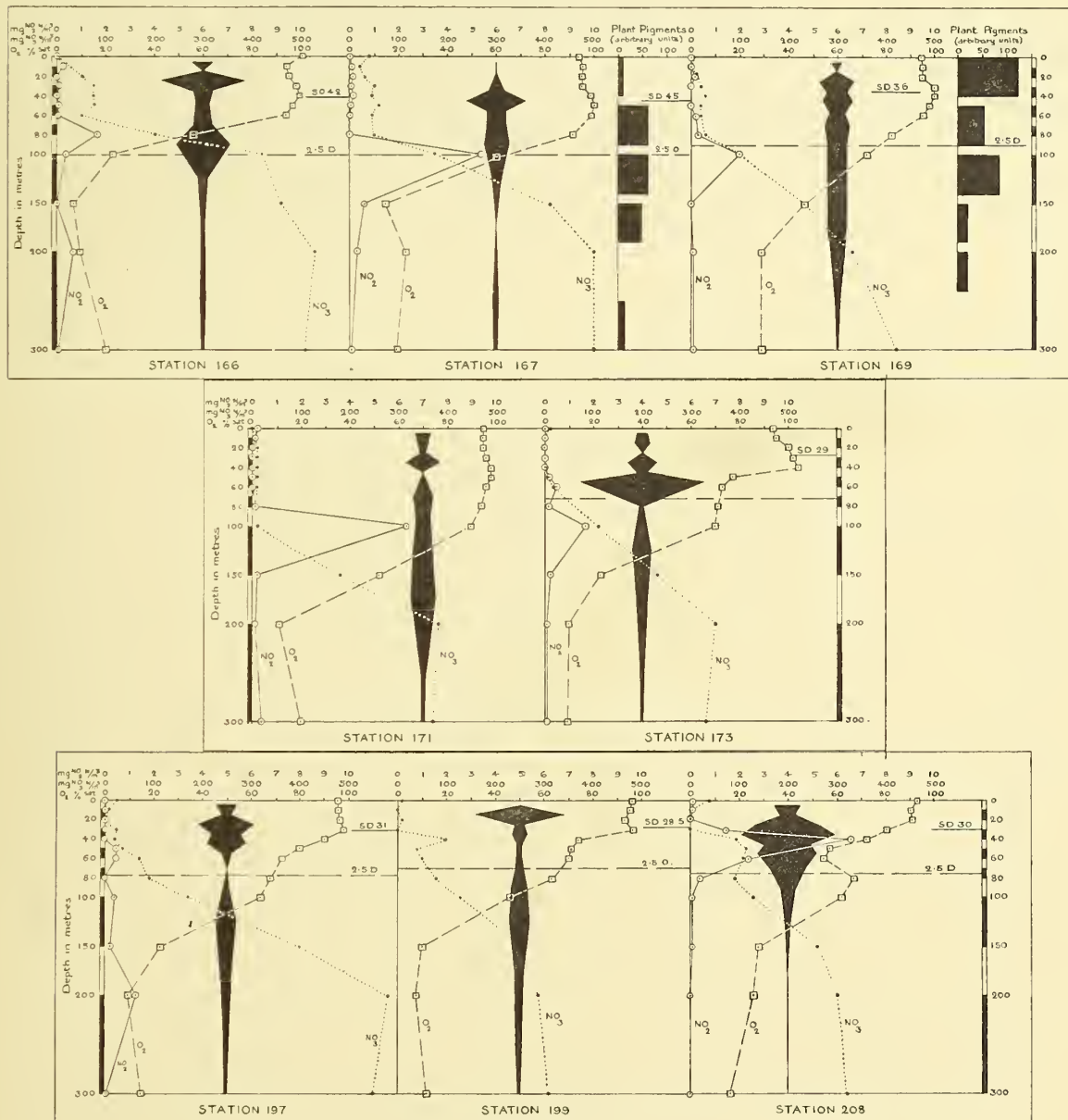
Station 166 is complicated by a layer of lighter water, which again probably originated in the region east of Ceylon, and was carried north by the coastal current of the NE monsoon season (Hornell and Ramaswami Nayudu, 1923). Utilization is incomplete even in the 20–60 metre layer, indicating probably an influx of water from a lower level elsewhere. Traces of the same influence are also to be found at Station 167, where, however, depletion had proceeded further in the uppermost 80 metres. The high nitrite at 100 metres is evidently connected with the relatively dense plankton population.

Station 169 is on the Carlsberg ridge, and its rich plankton is due to an upward movement of deep water. This movement is apparently a slow one, so that the supply of nutrients is not in excess of the consumption by the plankton. Thus its effect does not appear in the chemical picture, unless the slight nitrate peak at 40 metres is due to this cause.

At Station 171 a downward movement of water is indicated by the temperature, which was higher than at corresponding depths at Stations 167 and 169. Unfortunately the station was worked at night, and no Secchi disc reading could be taken, but it is unlikely that the water was clear enough to account for the almost complete depletion of nitrate as far down as 100 metres, which is probably also due to the sinking water. This same movement probably explains the fact that there was no great plankton production in progress, but a considerable amount of debris decomposing about the 100-metre level, since organisms would tend to be carried rapidly down below the compensation point.

Station 173 shows the profound influence of the strong currents in that region. The surface layer above the sharp boundary at 50 metres is water of relatively low salinity, which had come north with the African coastal current. The low oxygen and pH coupled with low nitrate at 50 metres probably indicate a rich zooplankton or bacterial population.

The Arabian Sea as a whole is dominated by the alternation of the two monsoons, and is therefore far more seasonal than most tropical oceans. From the end of May to mid-September the high winds and stormy seas of the SW monsoon prevail. We have unfortunately no observations during this period, and it is impossible to say to what

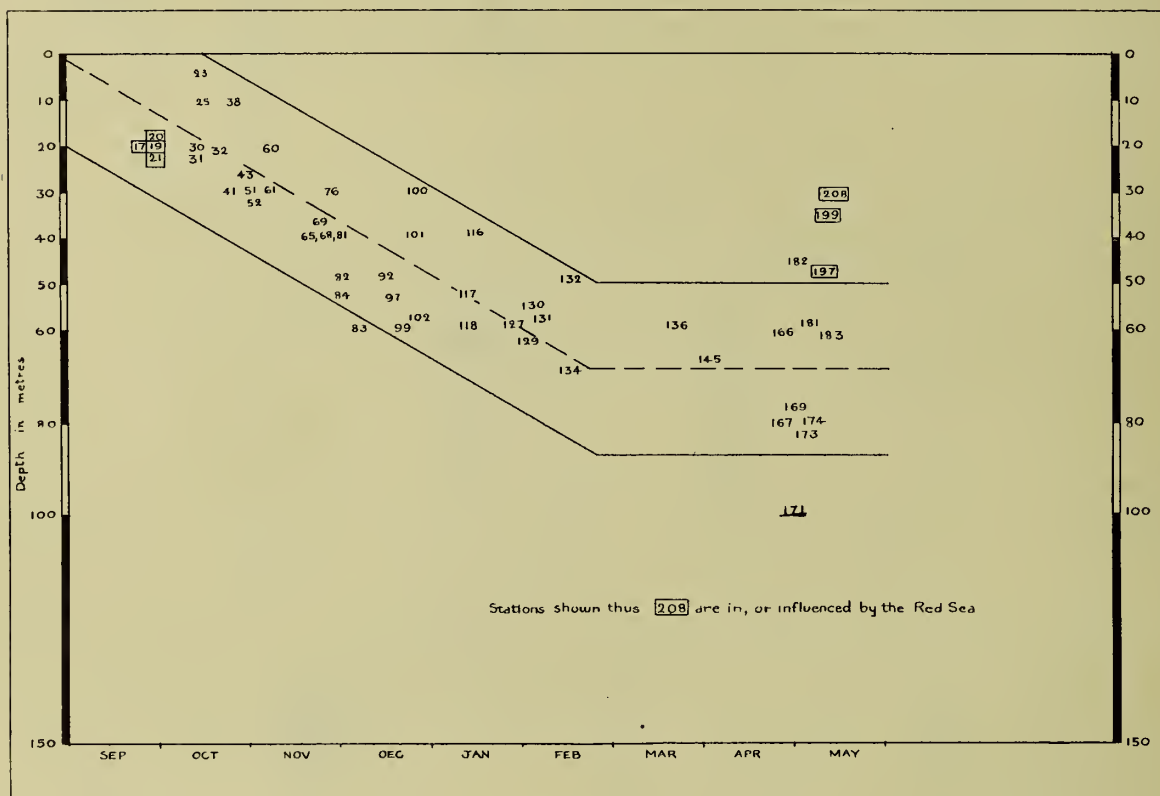


TEXT-FIG. 13.

extent stormy conditions retard the growth of plankton, or how deep mixing by the wind extends. It is, however, not improbable that a certain amount of nitrate and phosphate from the upper part of the thermocline is distributed through the surface layers. It should be noted here that the big outbursts of diatoms recorded in May off the Madras coast by Menon (1931), and off Calicut by Hornell and Ramaswami Nayudu (1923), are the direct result of the rains brought by the SW monsoon. They are perhaps partly due to dissolved

substances washed out from land, but are probably also the result of the lowered salinity and consequently increased stability of the surface layers. These outbursts are probably confined to the inshore waters, and would not be expected to occur in the open sea or in the Gulf of Aden region, where the monsoon brings little or no rain.

We may suppose that with the resumption of calm conditions in September, considerable growth of phytoplankton is initiated, but owing to shortage of supplies of nutrient salts this is mostly over by the end of January. From then on plankton is comparatively sparse except where upward water movements cause renewal of nutrient salts. This occurs principally in the strong currents near the African coast about  $1-3^{\circ}$  N.,



TEXT-FIG. 14.

near the Seychelles bank, and in a smaller degree over the Carlsberg ridge, which runs from NNW to SSE, down the centre of the basin.

It must be emphasized that the picture given here of the plankton cycle must of necessity be incomplete, founded as it is largely on chemical data unsupported by direct seasonal observations.

Text-fig. 14 shows the influence of the calm period of the year in widening the limits of the productive zone. The depth of its lower limit, as estimated from the nitrate and oxygen figures, is here plotted against time, the points being indicated by the station numbers. The diagram shows that there is a general downward movement lasting till about the end of February, after which conditions remain more or less constant. Of the stations which fall outside the lines ruled on the diagram, the one in the Red Sea and the two at the western end of the Gulf of Aden (197, 199 and 208) clearly belong to a



different system, and are not comparable; at Station 182 we have already seen that there is a strong upward movement of water, and conversely a downward one at Station 171.

This deepening of the productive zone gives us the means of making a rough estimate of the phytoplankton crop. Thus in the five months between the end of September and the end of February there was, on the average, a fall of 55 metres in the lower limit of the productive zone. Now the average nitrate content of the 60-metre layer at eight stations at the beginning and eight at the end of this period was 290 and 30 mg. N/m<sup>3</sup> respectively. The change therefore represents the consumption of at least 200 mg. NO<sub>3</sub>-N/m<sup>3</sup> in a layer of water 55 metres thick. Assuming nitrogen to form 0.5% of the wet weight of phytoplankton (Cooper, 1933*b*), this implies the production of 2.2 kg. of algal material (wet weight) per square metre of sea surface in 150 days, or a production rate of 14.4 gm./m<sup>2</sup>/day.

This value is only to be regarded as the roughest of approximations. For the rich area at the mouth of the Gulf of Aden it is certainly too low, since no account of the upward water movements has been taken. On the other hand it is almost equally certainly too high for most of the Arabian Sea, since nitrate concentrations as high as 200 mg. N/m<sup>3</sup> are probably never found there within 20 metres of the surface.

When compared with other areas (see pp. 30, 31), the production rate is rather surprisingly high. Except for the upwelling areas, the figure reached probably represents the major part of the year's production, since there seems to be little further growth after the end of February owing to exhaustion of the supplies of nutrient salts, and growth is probably not very rapid during the stormy season of the year. Even if it represents a fair average for the whole annual production, it seems high compared with the English Channel figures (1.4 kg./m<sup>2</sup> as calculated by Atkins and Cooper), in view of the fact that the highest plankton population recorded (Station 101—an upwelling area) is only a little more than a tenth of the maximum recorded by Harvey (1934*b*) during the spring outburst, and the lowest (Station 132—average 31.5 units/m<sup>3</sup>) is 25% lower than all but one of his records, and less than a tenth of the population generally present during a great deal of the year in the waters off Plymouth.\* It is of interest that the figure for the rate of production is of the same order as that calculated by Seiwel (1935*a*) for the western part of the tropical North Atlantic. Whatever the value of the comparison, it is probably safe to say that the productivity of the tropical upwelling areas exceeds that of any temperate sea, while the open tropical ocean is by no means as barren as has commonly been supposed, and is indeed comparable in this respect with a region such as the English Channel.

## V. THE NITROGEN CYCLE.

### (1) INTRODUCTORY.

It has long been known (Brandt, 1899, 1902, 1920; Harvey, 1920, 1928*b*, etc.) that the deep water of the great oceans contains a vast store of nitrate. As the most highly oxidized form of combined nitrogen this is also the most stable, and therefore the only form in which it persists for long periods in the sea. Since by far the greater part of the combined nitrogen in the sea exists in this form, it is perhaps not surprising that the

\* It is probable that a larger proportion of the tropical plankton escapes the silk net than is the case in temperate regions.

photosynthetic organisms are adapted for its consumption as their principal source of supply, although some at least can also obtain their nitrogen from nitrite, ammonium salts, and even from simple organic compounds such as glycine (Schreiber, 1928 ; Braarud and Klem, 1931 ; Harvey, 1933).

As has been emphasized in the literature, the cycle  $\text{nitrate} \rightarrow \text{plants} \rightarrow \text{nitrate}$  is a closed one in the sea in general, except in a few places such as the Norwegian fjords and other land-locked seas, where the proximity of land provides an external source of supply. There is also in most places the possibility of supply by precipitation from the atmosphere, but this can be shown to be negligible. Thus on the basis of Braadlie's (1930) analyses of rain and snow, Braarud and Klem (1931) calculate that off the Norwegian coast the total annual addition of combined nitrogen from this source to the uppermost 10 metres of the sea would not increase the concentration in the water by more than 7 mg./m<sup>3</sup>. It is possible that in some tropical regions with a high rainfall from thunderstorms this might be exceeded, but it is most unlikely that even as much as this small amount is added to the waters of most of the open oceans from this source.

So far we have two points in the cycle—nitrate and phytoplankton. We have seen from the fact that nitrate in temperate regions shows seasonal changes complementary to those of the phytoplankton population, and from the fact that plankton is especially abundant in regions where upwelling of deep water produces rich supplies of nitrate, that the link between these two stages is a close one. We must now consider the other side of the circle, and the stages which intervene between the death of the plankton and the return of its nitrogen to the stores of nitrate.

Here the main agents in the chain of transformations are the bacteria. A number of investigators have attacked the problem at various times, and with varying degrees of success, so that our knowledge is somewhat scattered, and the value of some of the earlier work is hard to estimate. Recently Waksman and his collaborators at Woods Hole have brought the methods of soil bacteriology to bear on the problem, and have contributed much to the understanding of previous work, which was often apparently contradictory. In a recent paper (Waksman, Hotchkiss and Carey, 1933) they have reviewed previous work, and summarized present knowledge of the part played by bacteria in the nitrogen cycle, and much of what follows here on the bacterial aspect of the problem is based on their paper.

On the death of the plants, or of the animals which feed on them, the complex organic compounds into which they have built up the nitrogen assimilated as nitrate are attacked by bacteria, which break them down into simpler organic compounds such as amino-acids and amines, and finally to ammonium compounds. This ammonia is then usually oxidized by other bacteria first to nitrite and finally to nitrate. So much for the direct cycle, but there are also various side branches. Thus the nitrate, if not already consumed by phytoplankton, may, under certain conditions, be reduced by other bacteria to nitrite, ammonia or gaseous nitrogen or its oxides. Other bacteria in the presence of carbohydrates may compete with the plants for the available inorganic nitrogen, and convert it into organic complexes. Finally, yet other bacteria fix atmospheric nitrogen, and build it up into the organic compounds of their own body substance.

Bacteria are thus concerned with five different processes all involving the transformation of nitrogen compounds : (1) Liberation of organically bound nitrogen as ammonia ; (2) oxidation of ammonia to nitrite and nitrate ; (3) reduction of nitrate to nitrite and



free nitrogen ; (4) synthesis of inorganic nitrogen into organic compounds ; (5) fixation of atmospheric nitrogen.

## (2) AMMONIFICATION OF ORGANIC MATTER.

This aspect of marine bacteriology has been very much neglected, the interest among earlier investigators having been mainly focused on the nitrifying and denitrifying forms, or on the distribution of bacteria of all sorts. The most valuable contribution is that of Waksman, Carey and Reuszer (1933). They found that zooplankton material was rapidly decomposed, with liberation of about half the nitrogen as ammonia, in both sea-water and mud media. More  $\text{CO}_2$  was produced in the mud cultures, and it is suggested that, whereas the proteins are decomposed equally in both media, other constituents poor in nitrogen, such as chitin, or nitrogen-free, such as certain fats, are more readily attacked by the bacteria of the mud. The decomposition of algal material was found to depend similarly on its composition. Material rich in nitrogen, such as *Ulva* (ca. 2% N dry weight, salt-free basis), decomposed both in water and in mud. On the other hand *Fucus* (less than 1% N dry weight, salt-free) was only very slowly attacked in the water, but decomposed rapidly in the mud medium. Addition of inorganic nitrogen sources favoured the decomposition of nitrogen-poor material in the sea-water, both nitrate and ammonium salts being readily usable to supply the nitrogen required for cell synthesis by the bacteria.

Thus decomposition of algal residues poor in nitrogen may result in a minimum of available nitrogen free in the water, while animal residues produce abundant supplies of ammonia. The bacteria responsible are present both free in the water and in the sea bottom.

Our knowledge of the distribution of ammonia in the sea is somewhat scanty. Since the distillation methods used have been shown to be liable to form ammonia by hydrolysis of organic compounds, the results reported by earlier workers cannot be implicitly relied upon. However, such data as we have tends to support the view that ammonification is largely a surface and to some extent also a bottom phenomenon.

Thus Brandt (1920) showed that in the tropical Atlantic ammonia exists principally in the subsurface layers, and that it is much less abundant in regions where upwelling water brings tongues of water up from the depths. Böhnecke, Hentschel and Wattenberg (1930), in the water west of Iceland, found the ammonia profile to be an almost exact mirror image of the nitrate profile, indicating that consumption of nitrate in the surface layers by the plankton is followed by ammonification in the same layers. Robinson and Wirth (1934a) in the Puget Sound region found a rather irregular distribution, which differed in that the maximum tended to be well below the surface. Similar results are reported by Braarud and Klem (1931), who found that off the Norwegian coast there was a tendency for a maximum in the 40–70-metre layer and a minimum at the surface. In the deep water off Vancouver Island (Robinson and Wirth, 1934b), what ammonia there was, was nearly all in the uppermost 100 metres, the average values being 20 mg.  $\text{NH}_3\text{-N/m}^3$  at the surface and 2 mg./ $\text{m}^3$  at 1500 m. There the shallow inshore stations contain more ammonia, and an especially high concentration was found at the bottom of a submarine gully, owing to stirring up of the mud.

Cooper's (1933a) results for the English Channel also support the same view. In



winter he found a maximum near the surface, a minimum in mid-water, and intermediate values at the bottom. In spring the surface values decrease, which it is suggested is due partly to consumption by the plankton, and partly to lack of supplies of organic matter owing to the sparse plankton production during the winter months. Later a general rise occurs in summer and autumn towards a maximum of about 30 mg. N/m<sup>3</sup>. High ammonia concentrations are often found near shore owing to land drainage, especially where the sewage of a big town is discharged.

Unfortunately, owing to lack of time and laboratory space on board, ammonia determinations were not found possible on the John Murray Expedition, so that little is known about the distribution of ammonia in the open oceans. Such attempts as were made indicated that where any ammonia was present at all, it was in the uppermost 100 metres.

In general, then, the distribution of free ammonia in the sea accords with what we might expect from the bacterial distribution reported by Waksman, Carey and Reuszer. Ammonification is carried on immediately on the death of the organisms by bacteria which are present among the plankton. In shallow water a certain amount of nitrogenous organic matter may reach the bottom undecomposed, and ammonification may proceed there, but in deep water the organic nitrogen is nearly all liberated before reaching the bottom.

### (3) NITRIFICATION.

The process of oxidation of ammonia through nitrite to nitrate has been the subject of a good deal of research, but since the bacteria concerned are very sensitive to environmental conditions, and are not easily cultured, the negative findings of some of the earlier investigators must be regarded with some suspicion.

The presence of nitrifying bacteria in the sea was first suggested by Vernon (1898), and was demonstrated in mud, but not in the water of the Baltic by Baur (1902). Gran (1903) failed to confirm this in the Norwegian fjords, finding them only close to the shore, and Nathansohn (1906) found none in the Gulf of Naples.

Brandt (1902) had previously argued that if nitrate comes into the sea from the atmosphere or from land, we should expect to find it most abundant in the surface layers which is contrary to the facts. He therefore argued from its abundance in deep water that nitrification occurs chiefly at or near the bottom.

Thomsen (1910) found nitrite-forming bacteria abundant in all bottom samples from Kiel Fjord, Heligoland, and the Gulf of Naples, but absent from sea-water, plankton or fixed algæ. Nitrate-formers were also found in mud samples, but only close to shore. The organisms responsible were isolated, and were found to be morphologically identical with the *Nitrosomonas* and *Nitrobacter* isolated by Winogradsky from soil, and to have similar high temperature optima. He attributed Nathansohn's negative results to unsuitability of the culture medium.

Issatschenko (1908, 1914) found nitrifying bacteria in the water of the Arctic Ocean; they were also found in bottom material from the Catherine coast, from the Northern Ice Sea, and from the high seas, but were absent from surface water. He found only nitrite-formers in the bottom material. Later (1926) he reported that nitrifiers were more abundant in sandy and shell-rich bottoms than in clay.

Lipman (1922) concluded that, although absent from the water of the open sea,

nitrifying bacteria are normally present in the sea bottom. Similar findings were reported by Harvey (1925, 1926, 1928*b*).

On the basis of these results Brandt (1927) considered it established that bacteria capable of oxidizing ammonium salts are completely lacking in surface water, but are present in the sea bottom.

Waksman, Hotchkiss and Carey (1933) as a result of a critical series of experiments reached much the same conclusion, namely that free sea-water, especially surface water, contains either no nitrifying organisms at all, or very few. On the other hand the sea bottom, whether mud or sand, contains an active population. Nitrite-formation in media containing ammonium sulphate was easily demonstrated, but it was not found possible to obtain formation of nitrate by direct inoculation into media containing nitrite. However, after longer incubation of the nitrite-forming cultures, nitrate formation could be shown, and inoculation of nitrite containing media from such old cultures gave rapid nitrate formation. The fact that it was much easier to demonstrate the formation of nitrite is attributed to the specificity of the organisms and the conditions of cultivation. Further results supporting their conclusions are reported by Carey and Waksman (1934).

As already mentioned, the abundant nitrate of all deep ocean waters points strongly to the bottom as at any rate the principal site of the nitrification process. In shallower water where there is vigorous mixing, at least at some time of the year, it is possible that these bacteria get carried up into mid-waters. This is probably the explanation of Cooper's (1933*a*) conclusion that nitrification proceeds throughout the water column, and his observation that an increase of ammonia is usually followed after an interval by an increase in nitrite, and later by an increase in nitrate, supports this view.\*

Deacon (1933, p. 234) remarks that nitrite is "a stage in the formation of nitrate from animal decomposition", and that "its absence from deep waters with the greatest phosphate and nitrate is surprising". It is, however, probable that nitrate formation in the sea is a very much more rapid process than it was in Waksman, Hotchkiss and Carey's cultures. The nitrate-forming organism isolated by Thomsen (1910) had a high temperature optimum, but there is no reason to suppose that it is the only organism present, or even a typical member of the population. It is indeed almost incredible, in view of the generally low temperatures prevailing at the bottom of the sea, that there are not other nitrifying bacteria in the marine muds, which are more closely adapted to their environment than this form whose characteristics fit it for life at the temperatures of land soils. The viability of such organisms would be likely to be low under laboratory conditions, and it is easy to see how culture experiments might fail to show rapid nitrification as a characteristic of marine muds. Furthermore, since nitrification is proceeding in the mud, the products presumably escape only by diffusion into the overlying water. Such a process is bound to be slow, and would allow time for the completion of the oxidation. Even if some nitrite does diffuse out into the water, its presence would usually escape notice, since the deepest samples collected are usually several metres above the bottom.† The general absence of nitrite in deep waters cannot therefore be held to indicate

\* See also Atkins (1930), where the same view is put forward.

† Rakestraw (1933) records finding both nitrate and nitrite much more abundant in water extracted from mud brought up in a grab than in water collected 3-4 metres above; the ratio of the two was much the same in both cases.



any different nitrification process. This is confirmed by its presence in the bottom water of shallow, relatively unstable seas such as the English Channel, where any which does escape from the mud will be carried up into the layers which can easily be sampled.

#### (4) REDUCTION OF NITRATE, AND DENITRIFICATION.

Owing to the early recognized importance of nitrate as a raw material for production of plankton, considerable interest has centred on those bacteria which destroy it. In considering the reported work of the earlier investigators, it is important to remember that there are three groups of bacteria included under this general heading: (a) those which reduce nitrate to nitrite only, (b) those which reduce nitrate and nitrite to ammonia, and (c) those which reduce nitrate and nitrite to free nitrogen and gaseous oxides of nitrogen. Only the last group are properly called "denitrifiers", since they alone cause loss of nitrogen from the system.

Nitrate-reducing bacteria were demonstrated in the sea by Beijerinck (1890), Fischer (1894), Russell (1893) near Woods Hole, and Vernon (1898) in the Gulf of Naples.

In 1899 Brandt put forward his famous theory that the nitrate-reducing bacteria control the supply of available nitrogen, and so the production of plankton. At that time he believed that the supply of nitrate came entirely from land, and that but for these bacteria it would soon reach a concentration in the sea which would be lethal for the plants and animals. It was observed that the plankton-rich temperate and arctic seas were also rich in nitrate, and he attributed the poverty of tropical oceans to their low nitrate content. This in turn he supposed to be due to the greater activity of denitrifying and nitrate-reducing bacteria at tropical temperatures.

The publication of this theory attracted interest to the problem, and many investigators reported the discovery of denitrifying bacteria in various parts of the world—*e. g.* Baur (1902), Nathansohn (1906), Köhl (1908), Gräf (1909), Issatschenko and Rostewzew (1910), Drew (1910), etc.

Feitel (1903) showed their presence in great abundance at all depths, but especially on the bottom or in water near it, where organic matter was abundant. He isolated forms in pure culture which were active denitrifiers, especially at low temperatures. The general occurrence of bacteria of these types, together with the fact that nitrate decreased with rising temperature towards the surface in tropical seas, was held to support Brandt's hypothesis.

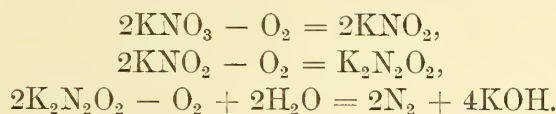
Gran (1901) isolated several nitrate-reducing bacteria, but he found that only close to shore, where abundant organic matter and nitrate are present, do denitrifiers play any important part in the nitrate economy of the sea. He considered Brandt's theory untenable.

Issatschenko (1914) found denitrifying bacteria capable of growing at very low temperatures (1–3° C.) in the North Polar Sea. He concluded that forms reducing nitrate to nitrite and ammonia were widely distributed, normal inhabitants of the sea, but he considered it doubtful whether the true denitrifiers, which are also widely distributed in northern seas, cause any considerable loss of combined nitrogen. Since they are active at low temperatures, and warm seas are also rich in nitrates in the lower layers, he also denied the validity of Brandt's views.

Cranston and Lloyd (1930) investigated the metabolism of a denitrifying bacterium



isolated from the sea (see also Lloyd and Cranston, 1930, and Lloyd, 1931). Their results can be explained by the assumption that the reaction proceeds in three stages, with intermediate formation of hyponitrite, thus :



Since each stage is completed before the next is begun, four-fifths of the oxygen available in the nitrate can be obtained without liberation of any nitrogen. Thus in the presence of abundant nitrate no gas is formed. The oxygen obtained by the organism goes to form  $\text{CO}_2$ , which combines with the  $\text{KOH}$  produced at the last stage, so that the medium goes acid at first, and finally alkaline.

It is thus possible that many of the forms which have been found only to reduce nitrate as far as nitrite are really facultative denitrifiers if given suitable conditions. Since, however, these include absence of oxygen as well as presence of a suitably small quantity of nitrate, it is unlikely that they are at all commonly realized in the sea.

That the bacterium studied by Cranston and Lloyd is not the only one concerned is indicated by its high temperature optimum ( $35^\circ\text{C}.$ ), since Issatschenko showed active denitrification at very low temperatures. It is also shown by the fact that in many cases denitrification is said to be favoured by good aeration (*e. g.* Gran, 1901), and by Waksman, Hotchkiss and Carey's (1933) experiments, where active denitrification was observed under aerobic conditions.

The latter authors confirmed Issatschenko's conclusion that forms reducing nitrate to nitrite are abundant in the water, and even more so in the mud. On adding an energy source such as algal material denitrification could easily be demonstrated, especially in mud cultures, but they consider it unlikely that this occurs to any great extent in the sea.

Denitrification and the reduction of nitrate to nitrite or ammonia are therefore processes requiring very special conditions. Not only is an abundant supply of an easily oxidized energy source, such as carbohydrate, necessary, but also an excess of nitrate over the requirements of the plants and the saprophytic bacteria of decay. As pointed out by Gran (1912*a*), such conditions may occur in enclosed fjords, where the organic matter is high at the bottom. In general the surface layers, which are richest in suitable organic matter, are too poor in nitrate, while the bottom water, which is rich in nitrate, contains comparatively little organic matter; what there is, like that of the mud, is mostly of an unsuitable type such as pentosans and polyuronides, which are only attacked by specific bacteria (Waksman and Carey, 1933; Waksman, Carey and Reuszer, 1933; Waksman, Carey and Allen, 1934).

There is, however, one level in the sea where a compromise may be found—at the lower limit of the photosynthetic zone. Here there is abundant organic matter,\* and since the growth of phytoplankton is prevented by lack of light, there is also ample nitrate available. We may therefore anticipate that in areas where there is any considerable production of plankton, the presence of nitrate-reducing bacteria would

\* This is supplied partly by the carbohydrate secreted into the water during the life of the plant cell (Braarud and Klem, 1931), and partly by the disintegration of dying organisms.

be reflected in a high nitrite concentration at this level. As we have already seen, this is normally the case in the open sea.\*

#### (5) BACTERIAL SYNTHESIS OF ORGANIC FROM INORGANIC NITROGEN.

Of this type of bacterial activity comparatively little is known. It probably comprises rather an aspect of the metabolism of various forms than any one group of bacteria.

We have already seen (p. 61) that the bacteria which break down organic residues can, when the substrate they are attacking is poor in nitrogen, obtain supplies for the synthesis of their own body substance from the inorganic nitrogen compounds in the water. Bacteria of this type, which decompose specific algal constituents, have been studied by Gran (1901), and recently by Waksman, Carey and Allen (1934), but little attention has been paid to their nitrogen metabolism. Besides these specialized forms there are probably many generalized saprophytes, which live among the plankton on the carbohydrates and other products of metabolism, obtaining their nitrogen partly from inorganic sources.

#### (6) NITROGEN-FIXING BACTERIA.

Benecke and Keutner (1903) were the first to demonstrate both types of nitrogen-fixing bacteria in the sea. The aerobic *Azotobacter* they found mainly on plankton, and the anaerobic *Clostridium* mainly in deep water and in the sea bottom. Keutner (1905) concluded that they are normal inhabitants of the sea, having been found in the North Sea, Indian Ocean, on the African coast, and in the Malay Archipelago. This has been repeatedly confirmed by later investigators, *e. g.* Keding (1906), Benecke (1907), Issatschenko (1908, 1914), Bavendamm (1932), Waksman, Hotchkiss and Carey (1933). Their especial abundance in the slime on *Zostera* and the shore algæ as well as among the plankton has led to the suggestion of symbiosis, but there is at present no means of verifying this.

Like the denitrifiers, they require a source of energy as well as supplies of other nutrients such as iron and phosphate. Of the quantitative aspect of their part in the nitrogen cycle nothing is known.

#### (7) INORGANIC INFLUENCES.

Besides the activities of the various types of bacteria known to be present in the sea, it has been suggested that certain transformations may be brought about by inorganic means.

Thus Darnell-Smith (1894) suggested that the oxidation of ammonia to nitrite and nitrate might be carried out by oxygen given off in a "nascent" state by photosynthetic organisms. He described experiments in which sea-water, allowed to stand, increased in ammonia content "by decomposition of organic matter". If *Ulva* was then put into the water, in the light a rapid fall in ammonia occurred, in the dark a less rapid rise. A very much slower fall in ammonia content was caused by aeration of the water without any *Ulva*. That the rise in ammonia was due to the decomposition of organic matter is probably correct, and supports the view, already expressed, that ammonifying bacteria

\* Since writing the above, I have discovered that Rakestraw (1933) suggests the same origin for the nitrite found about the 40-metre level in the Gulf of Maine.



are generally present. But the inference that the fall in the presence of *Ulva* in the light was due to oxidation by nascent oxygen seems unwarranted, since it is well known that ammonia can serve as a nitrogen source for algæ, and as the water was probably surface water, it may well have contained little nitrate. The fall in ammonia on aeration is also easily explained. If the air used was freed of ammonia, as was presumably done, the partial pressure of ammonia in the alkaline sea-water would be greater than in the air, with resulting loss to the air-bubbles as they passed through the water. Finally there is no evidence that the oxygen given off by plants is in a "nascent" condition.

Zobell (1933) has suggested that the same reaction may proceed photochemically. He found that flasks of sea-water to which ammonium sulphate had been added, if kept in the sun for a fortnight, showed a rise in nitrite and nitrate and a corresponding fall in ammonia, while controls kept in the dark remained unchanged. The reaction was unaffected by Berkfeld filtration, accelerated by manganese dioxide, imperceptible in distilled water or artificial sea-water, and abolished by autoclaving at 120° C. for half-an-hour. The effect was attributed to the ultra-violet rays, a mercury arc being more effective than sunlight. The water used is said to have given no growth of nitrifying bacteria on inoculation into Winogradsky's solution. The experiments so far reported are of a preliminary character, but light does appear to have influenced the reaction. The absence of nitrifying bacteria cannot be held to have been established, though the fact that Berkfeld filtration did not affect the result indicates that they were not the principal agents. This and the effect of autoclaving suggest the possibility of some thermolabile catalyst of an enzymatic character. A similar suggestion has been made by Kreps (1934).

Another photochemical reaction, again tending to form nitrite, but in this case by reduction of nitrate, has been described by Thiele (1907), and by Moore and Webster (1919).

In any case such reactions depending mainly on the ultra-violet can be of no importance except in the extreme surface layers, since it has been shown (Atkins, 1932) that the ultra-violet is very rapidly extinguished in the sea owing to scattering by small particles. Since the ammonia and nitrate concentrations in these layers are usually small, the magnitude of the effects cannot be large enough to play any considerable part in the nitrogen cycle. This is borne out by the fact that it is quite exceptional to find any demonstrable amount of nitrite at the surface.

#### (8) CONCLUSIONS.

Having briefly reviewed the various agencies causing transformation of nitrogen from one form to another, we are in a position to draw some conclusions on the cycle as a whole.

Nitrate forms the main store of combined nitrogen in the sea. In the algal cells it is built up into organic compounds—principally the proteins of their protoplasm. If the algæ are then eaten by animals the plant proteins are broken down by the digestive juices, and the amino-acids resynthesized into the proteins of the animal body. The animal phase may be prolonged through several stages, as small animals are eaten by larger ones, and they by larger ones again. Throughout there is a continual return of a proportion of the nitrogen to the sea as urea or ammonium salts in their excreta.



On the death either of the uneaten plant cell, or of any member of the animal chain, we start a series of bacterial transformations. The complex compounds are first of all broken down by the bacteria of decay through simple amino-compounds to inorganic ammonium salts. The ammonia, whether formed by these ammonifying bacteria, or set free in animal excreta, is then attacked by nitrifying bacteria, and oxidized, first to nitrite, and finally to nitrate.

In its simplest form the cycle is now complete. The synthesis of the nitrate nitrogen into the proteins of living matter proceeds in the illuminated zone, and the same is true in the main of the conversion from plant to animal proteins. The ammonification process appears to be carried out mainly in the same region by bacteria which live among the plankton, and partly also by bacteria living in the sea floor, and attacking the corpses which sink there from above. Nitrification, on the other hand, occurs almost entirely in the mud at the bottom. How the ammonia formed near the surface comes under the influence of nitrifying bacteria is not altogether clear. In the cooler parts of the world it may be carried down by convection currents, as suggested by Böhnecke, Hentschel and Wattenberg (1930), but this cannot occur over vast areas of the tropical and sub-tropical oceans. It may be that nitrification also proceeds in the sub-surface layers to a much greater extent than the experiments would suggest; the rapid rise in nitrate concentration at the lower limit of the productive zone lends some support to this view. Alternatively it is possible that ammonification goes on in deep water to a greater extent than has been supposed, and is masked by the rapid nitrification which follows. This would explain the presence of abundant nitrate in tropical deeps, but not the absence of large quantities of ammonia in the sub-surface layers. It is known that ammonia can serve as a source of nitrogen supply for the phytoplankton, but that it does not do so to any great extent in fact is indicated by the absence of pronounced seasonal fluctuations in the ammonia of the sea, such as are well known for nitrate, phosphate and silicate. It is, however, possible that such consumption of ammonia does occur in the tropics, where the plankton has a rather different composition, and where the absence of any marked seasons would make such consumption less easy to demonstrate. As we have at present no knowledge of the nitrogen metabolism of tropical plankton organisms, especially the Coccolithophoridae, or of the rate at which the bacterial transformations proceed at different depths and at different seasons, it is impossible at present to reach a satisfactory answer.

The activities of the other types of bacteria are probably of relatively minor importance, so far as the nitrogen cycle is concerned, although, as Waksman and his colleagues have shown, some of them are the main agents in the formation of "marine humus". How far the competition of the saprophytic forms living in the surface layers affects the production of phytoplankton it is impossible to say at present, but there is no doubt that they form a large part of the food of the smaller zooplankton (*cf.* Clarke and Gellis's [1935] experiments on the nutrition of Copepods).

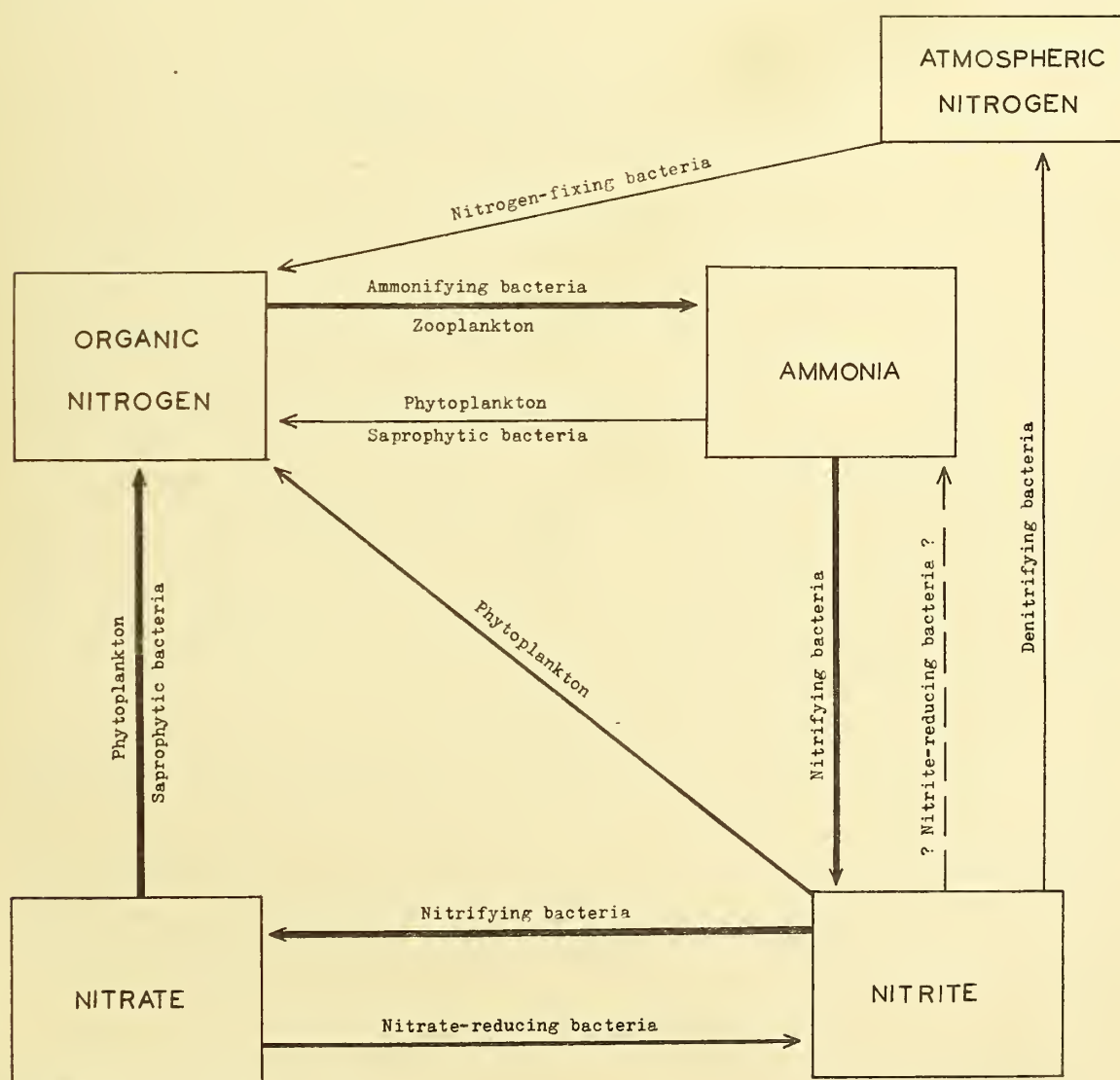
Since nitrite is readily assimilable by the plants, the nitrate-reducing bacteria, which we have seen to be active at the lower limit of the productive zone, do not affect the supply of available nitrogen.

Further evidence that the activities of the denitrifying and nitrogen-fixing types are not quantitatively of any great importance is given by Redfield (1934). Comparing the concentrations of nitrate and phosphate in sea-water from various places and depths with

simultaneous observations of the oxygen and carbon dioxide (calculated from the pH), he shows that carbon, nitrogen and phosphorus vary together in the sea in the approximately constant ratio  $C:N:P :: 140:20:1$  atoms or  $100:16.7:1.85$  gm. The correspondence for open sea data from polar, temperate and tropical regions is good, but the ratios are variable in regions subject to land influences and disturbance by water movements, such as the English Channel and the Norwegian Fjords. The average of a number of plankton analyses taken from various authors gives the ratios  $C:N:P :: 100:15.4:1.88$  gm. for the composition of plankton.

The general agreement indicates that the amounts of nitrate and phosphate present in the sea are controlled, in the main, by the same agency—the consumption by the phytoplankton and regeneration from its remains. If Brandt's theory that nitrate is controlled by denitrifying bacteria were true to any considerable extent, this would not be so.

The nitrogen cycle, as far as it is known at present, may be summed up in a diagram (Text-fig. 15).



TEXT-FIG. 15.

## VI. SUMMARY.

1. The conditions for the production of plankton in the sea are discussed in the light of present-day knowledge.

2. An account is given of a preliminary investigation of the metabolism of cultures of marine plankton diatoms. The consumption of nutrient salts proved somewhat variable. A rapid increase in nitrite was observed whenever a culture began to die off.

3. The distribution of nitrate and nitrite in the area covered by the Expedition is described, with special reference to the upper 300 metres of the water column. The figures are discussed in detail in conjunction with oxygen, stability, transparency and phytoplankton data, especially in their bearing on the production of plankton in the area.

4. Our knowledge of the nitrogen cycle in the sea is reviewed and discussed in the light of recent bacteriological and other investigations.

## APPENDIX: ANALYTICAL METHODS.

## I. DIATOM COUNTS.

The following methods were used in estimating the diatom population of experimental cultures:

(a) When the culture was young, and diatoms relatively few, 11 ml. were measured into a tapered centrifuge tube, and centrifuged for 10–15 minutes. About 10 ml. were then pipetted out, and the remaining 1 ml. centrifuged again for a further 5 minutes. The supernatant fluid was then carefully removed with a fine pipette until 0.1–0.2 ml. remained. This was stirred and transferred with the pipette to a slide, and the whole counted under a  $\frac{2}{3}$ -in. objective. The losses in this procedure have been shown by Gran (1929a) to be about 10%, and the 11 ml. are therefore calculated as 10.

(b) As the cultures became denser, the numbers to be counted by this method became inconveniently large, over 4000 cells per sample being counted on one or two occasions. This was extremely fatiguing and time-consuming, and some way of reducing the numbers was sought. Accordingly in a few cases 1 ml. of the culture was added to 10 ml. of filtered sea-water in a centrifuge tube, and treated as above.

(c) In many cases, where the population had risen to 1000 or more diatoms per ml., the simpler procedure was adopted of measuring 0.1 ml. direct on to the counting slide with a graduated pipette. Such counts were always made in duplicate, and when time allowed, in triplicate.

(d) In experiments with *Nitzschia closterium*, where the cells are exceedingly small and the numbers large, counting was done with a Thoma hæmacytometer slide (kindly lent me by Mr. H. W. Harvey), in which the volume over the ruled area was 0.1 c.mm. Such counts were usually made in triplicate, more being done in some cases, so that at least 400 cells were counted from each sample.

Individual counts did not usually differ by more than 15%, and the errors as a whole are believed not to exceed 10%.



## II. NITRATE.

Nitrates were determined by the Denigès-Harvey method, using reduced strychnine in sulphuric acid (Harvey, 1928 ; Cooper, 1932).

The reagent for the John Murray Expedition was made up in July, 1933, at the Plymouth laboratory according to the directions given by Harvey. In all, four reductions were carried out, each of 10 gm. of strychnine sulphate, 750 gm. of zinc, and about 1 litre of hydrochloric acid added in portions of 100 ml. or less at intervals of 3–4 hours. The reaction flask was heated meanwhile in a boiling water bath on an electric hot-plate. Of these the first was found to have too large a blank value, and was rejected. The others were mixed in portions with 10 times their volume of “nitrogen-free” sulphuric acid, and decanted into the original acid bottles (about 700 ml.) when the zinc sulphate had been allowed to settle.

The acid obtained for the purpose from Messrs. British Drug Houses Limited proved to contain a certain amount of nitrate, so that the finished reagent had a considerable blank value. I am much indebted to Dr. W. R. G. Atkins for lending me a quantity of an old batch of better acid, thus enabling me to prepare a small quantity of reagent with a very small blank, for use where a low nitrate concentration was expected. I also received much help and advice in the preparation from Dr. Cooper.

It was found that the blank value of the resulting reagent is greatly affected by the time which elapses between the completion of the reduction process and the addition of the sulphuric acid. Provided the addition is made immediately the reduction is complete, it is unnecessary to take great precautions to exclude nitric fumes during the reduction process, since any nitrate which finds its way into the mixture is immediately reduced by the nascent hydrogen. This is believed to be the reason for the appearance and subsequent rapid disappearance of the “pink flush” described by Harvey at each addition of hydrochloric acid to the reduction flask.

In use, 5 ml. of reagent was added to 4 ml. of each sample in small stoppered bottles, which were then stored on their sides in the dark. It was thus found possible to pour the clear liquid into the colorimeter cup without disturbing the slight precipitate of calcium sulphate which nearly always forms. Eighteen to twenty-six hours later the colour was measured in arbitrary units by comparison with a standard solution of safranin in a Leitz Duboscq colorimeter.

At least once during the use at sea of each bottle of the reagent, a calibration curve was constructed by determining the colour developed by known amounts of nitrate added to surface sea-water containing very little or none. Plotting “colour units” against nitrate content then normally gives a linear relation up to 300 or 400 mg. nitrate-N/m<sup>3</sup>. From the slope of the graph so obtained a factor was derived, which was used to convert “colour units” into nitrate content after subtraction of a blank correction. Where the linear relation did not hold, values were read off direct from the curves. Both factor and blank correction were found to vary considerably between different batches of reagent, but between bottles of the same batch the differences were slight.\*

As the distilled water prepared on board always seemed to contain considerable

\* Sund (1929) investigated the temperature characteristics of the colour reaction, and found that the colour developed is affected by the temperature. In the ship's laboratory temperature was nearly constant, and as the samples and standards experienced similar conditions, no correction has been applied.

quantities of nitrate, some difficulty was experienced in determining the blank correction. However, as each batch of reagent was found to give fairly constant low figures for surface and 10-metre samples at a number of different stations, this minimum value was taken to indicate complete absence of nitrate, and was applied as a blank correction to the other readings. There is therefore the possibility that the absolute amounts of nitrate recorded are slightly too low throughout, but this does not affect the relative accuracy of results in the depth series.

As fatigue was found at times to reduce the accuracy of the eye in the rather cramped conditions of the ship's laboratory, errors somewhat exceeding 5% must be regarded as possible.

For the culture experiments a fresh supply of the reagent was prepared in Cambridge in November, 1934, and proved extremely satisfactory. The procedure was varied in that 5 ml. of reagent were added to 5 ml. (instead of 4) of the sample. This was done in 1-in. Monax test-tubes, which were then covered with glass stoppers to exclude dust. Colorimetry was done with the photo-electric colorimeter described below, so that no decantation of samples was necessary.

### III. NITRITE.

The standard Griess-Ilosvay method was used (Orr, 1926; Wattenberg, 1931), following the procedure described by Cooper (1933*a*), 4 ml. of the mixed reagent being added to about 100 ml. of the sample in the ordinary salinity sample bottles, of which a number were reserved for this purpose. The colour comparisons were made after 24 to 36 hours in a Sund colorimeter (Sund, 1931), using a solution of safranin in the wedge, and a pale blue glass in front of the lamp. A set of standards in surface sea-water was prepared at the same time as the samples from each station. Variations in the nitrite value of the wedge were small. With the 25-cm. colorimeter tubes used 0.1 mg.  $\text{NO}_2\text{-N/m}^3$  was easily detectable. By this method no blank correction is required except in calculating the nitrite value of the wedge, where it was applied when necessitated by the presence of traces of nitrite in the water used for the standards.

For the analyses in connection with the culture experiments the photo-electric colorimeter was also used. Since this instrument only requires 25-ml. samples, the reaction was carried out in 1-in. Monax test-tubes. At first the samples were left overnight for the colour to develop, but they were then found to absorb appreciable amounts of nitrite from the air of the laboratory. This was overcome by leaving them only two hours, which was found quite sufficient.

### IV. PHOSPHATE.

Estimations of phosphate in the culture experiments were made by the Denigès-Atkins method, with Kalle's (1934) modification of using only half the amount of molybdate reagent originally recommended by Atkins (1923, etc.). Comparison was made in the photo-electric colorimeter from 10 to 20 minutes after adding the reducing agent.

### V. AMMONIA.

It was intended to carry out routine ammonia determinations during the John Murray Expedition by the direct nesslerization method introduced by Wattenberg (1928)



(see also Cooper, 1933*a*). Preliminary experiments at Plymouth showed that this method is not without difficulties, however, and all attempts to use it at sea failed completely. The Witting-Buch method involving preliminary precipitation of those constituents of sea-water which interfere with the Nessler reagent (Witting, 1914; Robinson and Wirth, 1934*b*) was then tried, and promised to work well. But it was found that the time and laboratory space required were altogether excessive, and determinations (of rather doubtful value) were only made at two stations.

## VI. PHYTOPLANKTON MEASUREMENTS.

The water meter with its wooden jacket and the brass bucket for the bottom of the net were made by Messrs. Casella & Co. to Mr. Harvey's design, and did not differ essentially from those since described by him (Harvey, 1934*a*). The canvas mouth and the silk nets were supplied by the Plymouth laboratory.

In use the net was weighted below, so that although lowered with mouth open, it did not fish on the downward journey, which was made with the brake held on by an elastic cord. When it had reached the bottom of the column of water it was intended to fish, the winch was stopped, and the first messenger sent down the wire. This released the brake, and hauling was at once started, a stop-watch being started at the same time. A little before reaching the top of the desired column the second messenger was sent, and the winch then stopped until its arrival, at which moment the watch was stopped. The net being now throttled, and the brake reapplied to the meter, the apparatus was hauled to the surface and got back on deck. From the reading of the meter and the time taken for the haul the volume of water which had passed through the net could be calculated according to the calibration of the meter made by the National Physical Laboratory. A standard portion of the contents of the bucket was poured off after vigorous stirring into a jar and preserved with formalin. The rest was strained through a disc of bolting silk, and the plant pigments dissolved out in 80% acetone as described by Harvey. The standards used for the colour comparison were made according to his original formula as follows :

Potassium chromate 2% . . . . .	6 ml.
Chromic sulphate 1% . . . . .	40 ml.
Sulphuric acid . . . . .	a drop.

A solution containing 0.46 ml. of the above in 50 ml. contains 1 "colour unit" per ml.

After the return of the expedition the set of standards used was compared with Harvey's original set and found to agree exactly. The results here recorded are therefore directly comparable with his figures for the English Channel (Harvey, 1934*b*).

## VII. A PHOTO-ELECTRIC COLORIMETER FOR USE WITH FAINTLY COLOURED SOLUTIONS.

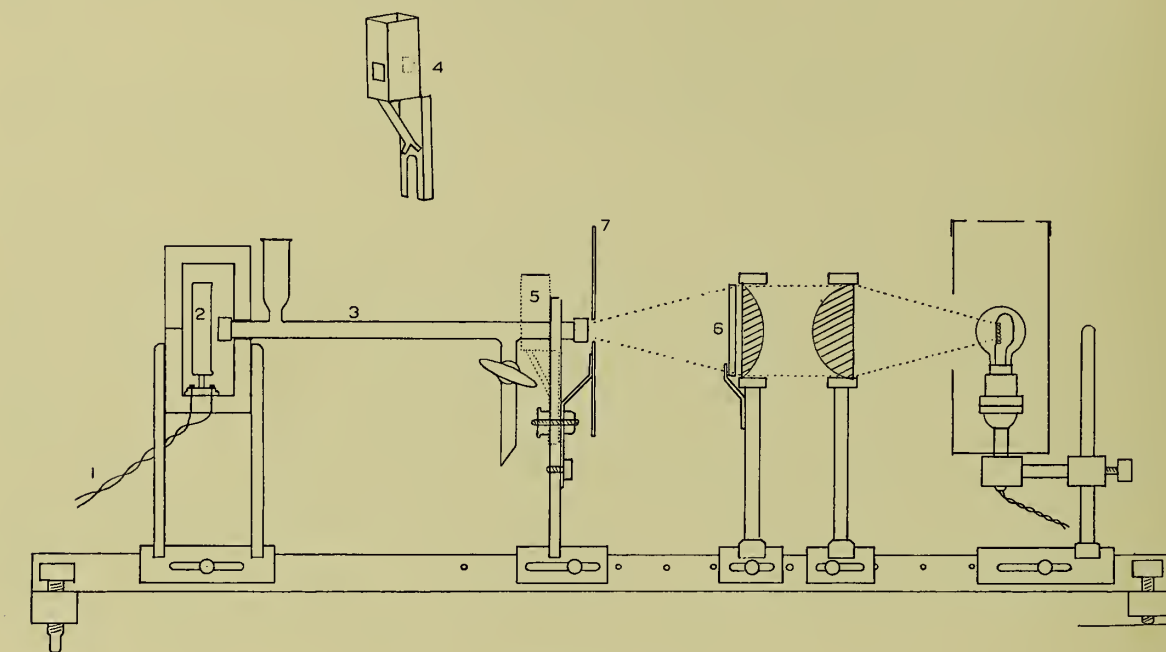
This apparatus was designed for the measurement of the very faint colours often met with in oceanographical chemistry, in order to increase both accuracy and speed of working, and at the same time reduce the considerable fatigue occasioned by a long series of optical comparisons.

It is based (see Text-fig. 16) on an optical bench made of a length of ordinary "angle



brass" mounted at the ends on cross-pieces of square brass rod, each of which carries two levelling screws. The bench carries a simple adjustable lamp-house, a condensing system of two lenses, the mounting of one of which also carries a light-filter, a fitting to carry one end of the glass colorimeter tube, and a light-tight wooden box, which carries the other end of the tube and contains a Weston "Photronic" photo-electric cell mounted in a radio valve-holder. A series of tapped holes along the bench and slots in the bases of all the fittings enable these to be clamped in any desired position by set-screws with knurled heads. The whole may be easily constructed in any reasonably well-equipped workshop.

The glass colorimeter tube is about 1 cm. bore, and has a tubulure 2 cm. from one end, and an outlet tube provided with a tap about the same distance from the other end ;



TEXT-FIG. 16.

it is painted black outside to keep out extraneous light. Any desired length of tube could be used, but 25 cm. has been found satisfactory for the depths of colour commonly met with in the analysis of phosphates and nitrites in sea-water. The ends of the tube are ground off square and smooth, and are closed by optically worked glass discs 15 mm. in diameter, such as Messrs. Leitz supply for the bottoms of their colorimeter cups. The discs are held in place by brass caps, which screw on to brass sleeves cemented to the tube with plaster-of-paris. To give the plaster a key on the glass, the outside of the tube is slightly roughened by grinding on a carborundum wheel for about a centimetre from the end. Shallow grooves are turned in the inside of the sleeve for the same purpose. If the end of the glass tube is carefully smeared with a very little tap grease before the disc is put on, there should be no difficulty in making a tight joint.

For use with strongly coloured solutions, such as are given by the Denigès-Harvey reagent for nitrate estimation, a fitting was made of thin sheet brass (see inset in the figure) to carry a 1-in. diameter test-tube in a vertical position. This clamps on to the

tube support when the tube is removed. Two square windows allow a beam of light to pass horizontally across the test-tube and into the box housing the photo-electric cell, which is brought up close. It was found a simple matter to select test-tubes which did not differ enough in bore to cause appreciable errors. The colour reaction is carried out in these tubes, which are then put into the apparatus in turn, thus avoiding all pouring of the acid solution from one vessel to another.

For light source an ordinary 12 v. 36 w. gas-filled motor-car headlamp bulb supplied through a transformer from the A.C. mains was found very satisfactory. The addition of a rheostat and an ammeter makes it possible to obtain constant illumination from day to day, and is desirable but not essential.

The photo-electric current may be measured by any suitably sensitive galvanometer of low resistance. The one used hitherto is a small one with a resistance of about 50 ohms and a sensitivity of  $2\mu\text{A}$  per scale division. Being intended for use as a null-point instrument, it has too short a scale, and is not ideal. One of the Cambridge Instrument Company's "Unipivot" instruments of similar sensitivity should be very satisfactory, and if suitably mounted, would allow the apparatus to be used on board ship.\*

Provided it is approximately complementary to the colour of the solution to be measured, the exact transmission of the light-filter used is immaterial. For phosphate determinations a "signal red" made by the Corning Glass Company has been used; for nitrate and nitrite a "signal green" made by Messrs. Chance Brothers.

The procedure in making a set of determinations is as follows: The appropriate filter is inserted, the tube filled with distilled water, and the light turned on some ten minutes before it is required to begin measurements. This allows the lamp filament to reach a constant temperature, and avoids a slight fatigue effect exhibited by the photo-electric cell in the first few minutes. The illumination is then adjusted so as to give exactly a full-scale deflection on the galvanometer, this being read as zero. The tube is then emptied, and the standards and samples poured in in turn, allowing a few seconds for drainage between each, and the reading taken in each case as soon as a steady value is attained. Each reading is thus the difference in galvanometer scale units between the deflection given by the sample and that given by distilled water.† At the end of a series the tube is again filled with distilled water, and the reading taken to make sure there has been no change in illumination.

Some care is needed to avoid the inclusion of bubbles when filling the tube. When the slope of the apparatus is adjusted to the minimum which gives effective drainage, it is found that after some practice a bubble is very rarely trapped in filling. When one is caught, its presence is always revealed by an unsteady or abnormally high reading. In changing from distilled water to sea-water samples, and *vice versa*, it is always necessary to rinse the tube carefully, or the turbulence caused by a mixture in the tube gives rise to considerable errors.

A fresh set of standards is prepared as usual for each set of analyses. The readings given by these normally lie on a smooth curve, when plotted against the concentration, and any faulty standard can thus be detected and ignored. Phosphate calibration curves hardly vary from day to day, and no blank correction should be necessary. In nitrite

\* Dr. W. R. G. Atkins disputes this statement.

† The fact that the illumination-current relation of the photo-electric cell is not linear is immaterial, since a direct calibration against known standards has to be made in any case.



analyses the curves are more variable, and blank corrections may have to be applied. In this case the blank may be due either to nitrite present in the distilled water, or to absorption of light by the reagent itself. In the first case the amount present is added to the values given to the standards, and the curve plotted accordingly; in the second case the same absorption is present in the samples, and no correction is therefore necessary.\* The two can be distinguished by preparing a second "zero" standard (distilled water), to which the reagent is added immediately before comparison, thus allowing no time for colour development. The difference between this and the "zero" standard prepared with the others gives the true blank due to nitrite in the distilled water. This is usually small or absent, while the "false blank" may be considerable, especially if the reagents are not very fresh.

In nitrate estimations the constancy of the colorimetric conditions may be checked each day on a set of permanent safranin standards, and the variations in the calibration curve so obtained should be extremely small. From this curve the samples for analysis can be read off in "colour units", and the constants required for converting these into nitrate concentration must be determined separately for each batch of reagent (Cooper, 1932).

Owing to small fluctuations in the mains voltage, and to the fact that the galvanometer used was not ideal, the accuracy so far attained does not exceed that of visual methods under good conditions, and is indeed not as great as that claimed by Kalle (1934) using the Pulfrich photometer. However, as he has shown that the errors inherent in the method as a whole exceed the colorimeter error, there is nothing to be gained from extreme accuracy in the colorimetry. The same is true of many colorimetric methods. The errors in the analyses so far carried out with the apparatus are approximately as follows: Nitrite  $\pm 0.1$  mg./m<sup>3</sup> for concentrations up to 10 mg. N/m<sup>3</sup>; phosphate  $\pm 2-3\%$ ; nitrate  $\pm 5\%$ .

The great advantage of the instrument is the enormous saving in time,† and especially in fatigue. It was observed that nitrate estimations could be carried out in approximately one-fifth of the time required with a Duboscq colorimeter. In this case the accuracy is probably also greater where a great number of comparisons have to be made, owing to the eye's loss of accuracy from fatigue. A considerable gain in accuracy is also to be anticipated in the case of bad colorimetric colours such as the yellow of Diénert and Wandenbulcke's method for silicates. The instrument has, however, the defect that errors are easily introduced by any turbidity in the solution. Thus in work on diatom cultures it was found essential to filter the samples.

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\* This effect gives rise to no blank value, when comparison is made by eye, since the "zero" standard and not distilled water is used as the basis for comparison.

† Dr. W. R. G. Atkins points out that there is no saving in time as compared with Helmer tubes. While this is probably so, most workers would find a considerable gain in accuracy.



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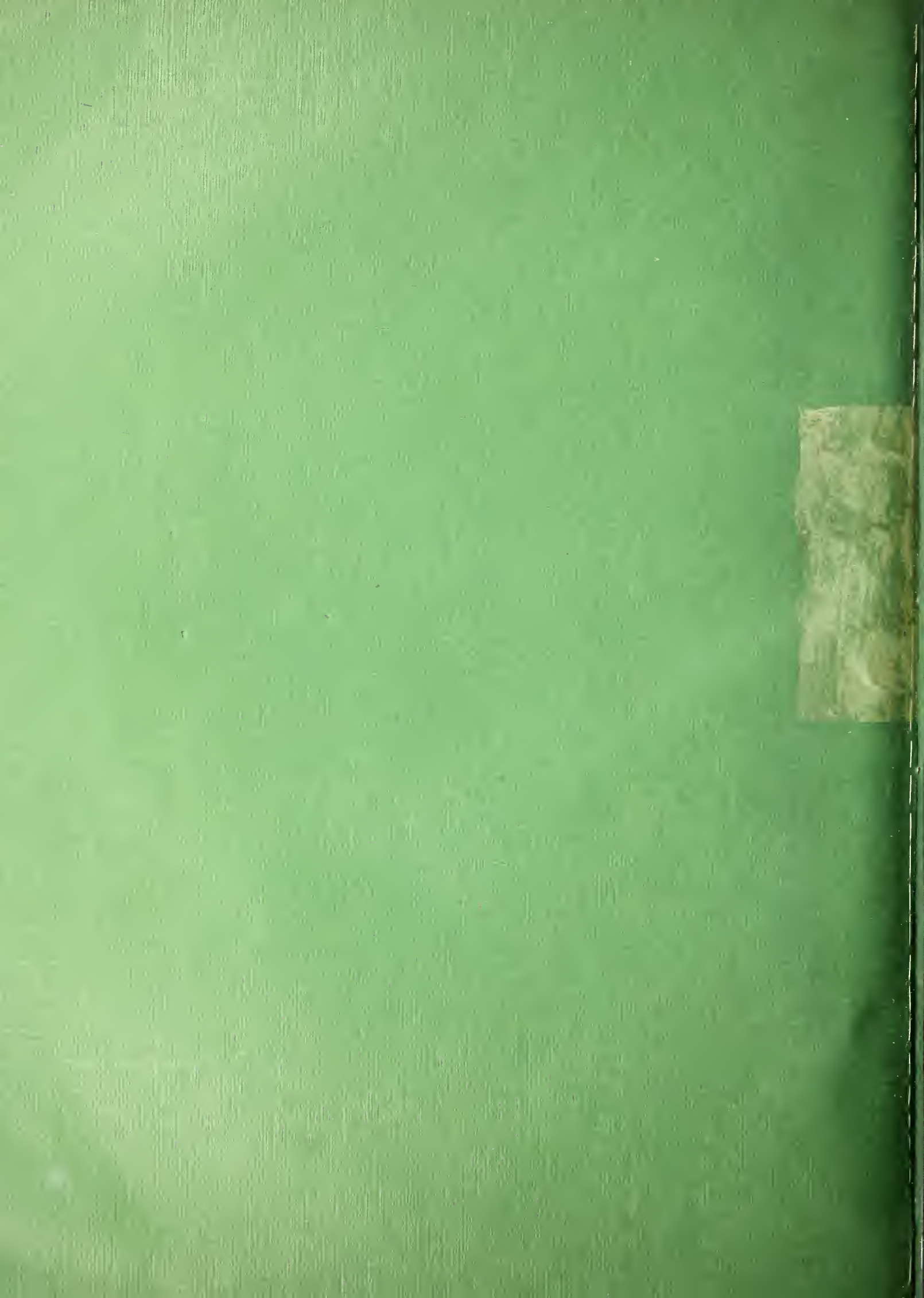
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INVESTIGATIONS

THE GENERAL HYDROGRAPHY OF THE  
RED SEA

BY

E. F. THOMPSON, M.Sc.(N.Z.), Ph.D.(CANTAB.)

WITH TWELVE TEXT-FIGURES



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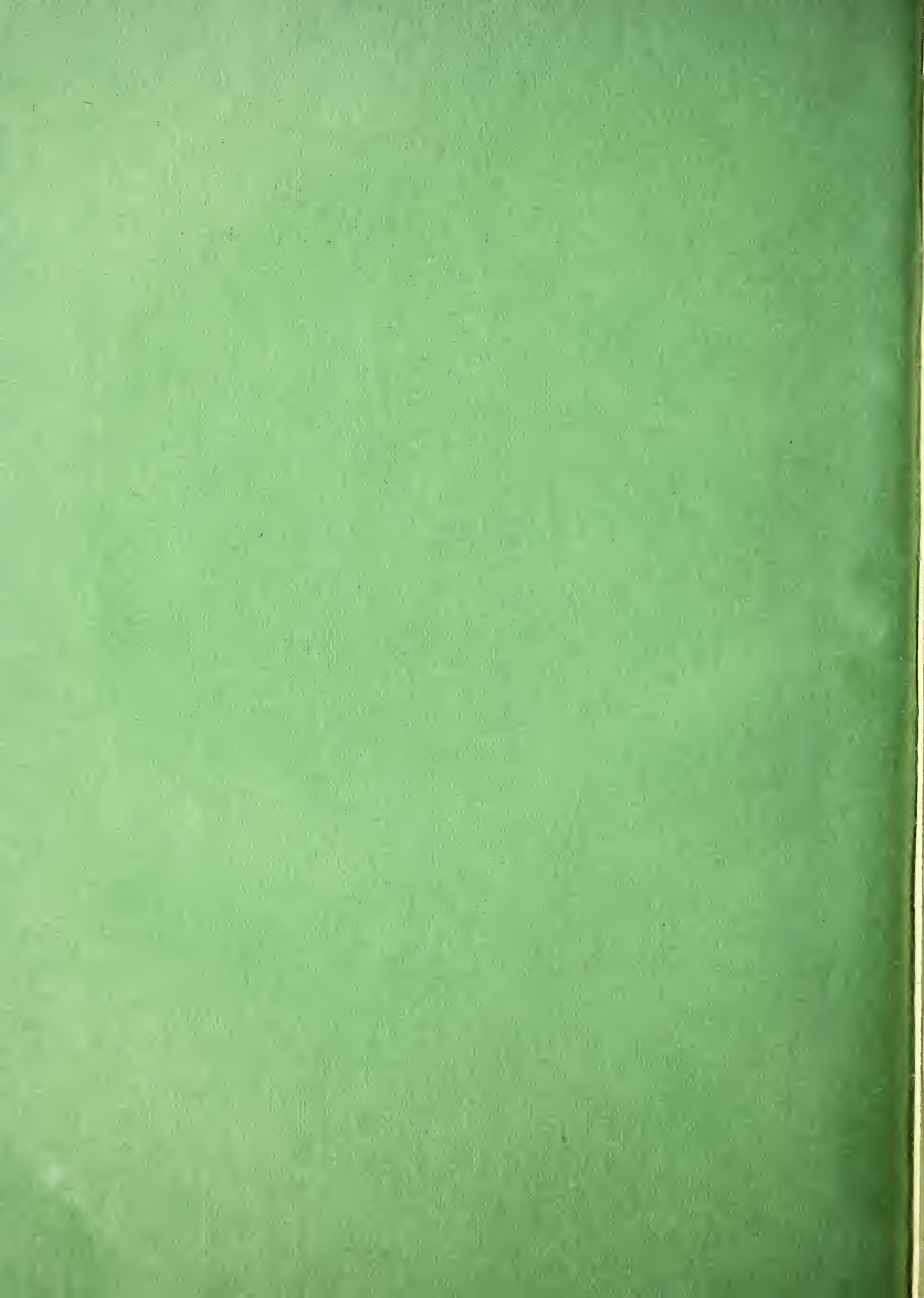
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# CHEMICAL AND PHYSICAL INVESTIGATIONS

## THE GENERAL HYDROGRAPHY OF THE RED SEA

BY

E. F. THOMPSON, M.Sc.(N.Z.), PH.D.(CANTAB.)

WITH TWELVE TEXT-FIGURES.

A CONSIDERABLE amount of hydrographic work has been done in the Red Sea ; but up to the time of the John Murray Expedition only two extensive series of observations had been published. Over a number of years the Italian Research Ship "Magnaghi" (Picotti and Vercelli, 1927) made a great many hydrographic observations in different parts of the Red Sea ; tide stations were established and current observations made in the Straits of Bab-el-Mandeb (Vercelli, 1930). In 1929 the Dutch "Snellius" Expedition (van Riel, 1932) worked three stations in the Red Sea itself, and one on the shallow ridge of the Straits of Bab-el-Mandeb. From the data they drew a section, but offered no explanation of the characteristic distribution. A discussion of the Red Sea circulation is given by Krummel, II, pp. 685-687 (1911). He recognizes a cross and horizontal circulation in the winter months, but assumes that the summer circulation is the same as that for the winter (see also Schott, 1929).

Much information as to the local currents and winds is given in the "Pilot" for the Gulf of Aden and the Red Sea, but as the information there recorded is so often concerned with very temporary and local conditions, it has been used here more as a check on the deductions from other data than as original information. Currents with a velocity of up to 3 knots are met with, especially in the southern part of the Sea. Many of the apparently contradictory reports of the currents observed are probably to be explained as due to the counter currents and anticyclonic eddies which are to be expected along the left-hand edge of such strong surface currents (Rossby, 1936, and Spilhaus, 1937).

The Egyptian Government have recently been engaged in hydrographic work, more particularly in the northern end of the Red Sea. Through the courtesy of their workers I have been enabled to see some of their unpublished material. In particular they have constructed a northern cross-section. As these results have not yet been published I have not actually used them in the present discussion ; but it is satisfactory to note that



they provide excellent corroboration of the conceptions here recorded and which were deduced before this information was available.

#### PHYSICAL CHARACTERISTICS OF THE AREA AND GENERAL DISCUSSION.

The Red Sea is a trough-shaped stretch of water about 1000 miles long, extending from the Sinai Peninsula to a few miles north of the Island of Perim. The average width is about 150 miles, and while the edges tend to be shallow and reef-bound, outside these the general depth is about 700 metres. The bottom is very irregular, and though depths of over 2000 metres occur in several places, it would seem that these great depths must be so isolated by submarine ridges as to be difficult to consider in anything but a very detailed study of this area. As will be seen later, the water below about 500 metres is so uniform in character that detailed consideration would seem unprofitable at this stage.

The climatic conditions need little discussion here. They favour a higher rate of evaporation than the average for this latitude. The rainfall is very small and a large amount of water is lost every year by evaporation and, as no large rivers find an outlet into the Red Sea, this loss has to be replaced by an inflow of water from the Gulf of Aden over the shallow sill near the Hanish Islands. In the rest of this account this shallow sill is referred to as the "Sill". There is no doubt that it marks the southern hydrographic limit of this area.

Water movements in the Red Sea are due to four causes: tides, winds, change of density and loss by evaporation. Of these, the most important are those produced by the winds, and these are the only ones which will be considered in any completeness here.

The wind systems in the Red Sea are comparatively simple. For half the year, from May to September, the winds blow almost directly down the length of the sea from the Sinai Peninsula to the Straits of Bab-el-Mandeb (*i. e.* from the NNW.). For the other half of the year (October to April) the winds from the Sinai Peninsula to about latitude  $22^{\circ}$  or  $21^{\circ}$  N. remain unchanged, but south of latitude  $20^{\circ}$  N. the wind direction is, on the average, completely reversed, now blowing up the Red Sea, *i. e.* from a SSE. direction. There is considerable fluctuation in the direction and force, but it has been shown (Fjeldstad, 1930) that the total transport of water can be derived from the wind resultant.

Let us consider the effects of such a wind system. Several workers, notably Ekman (1922, 1927, and 1928), have shown that in a homogeneous water, a steady wind will produce the following water movements:

(1) "A pure drift current," limited to the upper layers, in which the surface water moves at  $45^{\circ}$  *cum sole* from the direction of the wind; with increasing depth this deflection from the wind's direction also increases, while the velocity of the current decreases until it becomes negligible at the "level of frictional resistance". The result is a net transport of water at  $90^{\circ}$  *cum sole* from the direction of the wind.

(2) "A slope current," producing by the piling up of the water along the coasts by the pure drift current. Such a current runs with uniform velocity and direction from the surface to the "lower depth of frictional resistance", and is directed at right angles, *cum sole* from the direction of the slope.

(3) "A bottom current," part of the slope current, reaching from the "lower depth of frictional resistance" to the bottom, and turning *contra solem*, with increasing depth.

Ekman extended his consideration to cases where the depth was less than  $D$  (the



depth of frictional resistance), and where a coast-line interfered with the free movement of the wind current. He showed that in these cases the current would tend to move in the direction of the wind instead of to the right of it.

Some simple theoretical deductions have been made by Sverdrup (1933) in a consideration of such systems. It is sufficient here to state that certain factors, neglected by Ekman, tend to reduce the angle between the wind and the pure drift current, so that such a current has actually a component in the direction of the wind as well as at  $90^\circ$  *cum sole* from it; and further, that there seems to be considerable doubt as to whether a "slope current", in the sense in which this term is used by Ekman, is ever found in a non-homogeneous medium such as the sea. Such is the general system of water movements, which, according to Ekman, are produced by a wind in a homogeneous body of water.

Montgomery (1938), in discussing the conclusions of Palmen (1932), states: "Along a deep coast-line, a normal drift current is set up with its transport cross-wind; a longitudinal wind produces 'Windstau' of stream-effect type which sets up a gradient current. Along a very shallow coast-line frictional forces entirely outweigh the Coriolis force; the drift current is down-wind and a gradient current cannot exist. At intermediate depth, being the normal case, both types of 'Windstau' occur simultaneously, etc." Off the coasts of the Red Sea the water is generally of "intermediate depth", where the Coriolis force will be partly but not entirely outweighed by frictional forces.

We may take it, then, that the effect of a wind will be to cause a transport of surface and subsurface water to the right of the direction of the wind, and also, to a lesser extent, in the direction of the wind. In a narrow area such as the Red Sea, the importance of the second component will be relatively much increased, and considerable water transport will take place in the direction of the wind. At the same time the component at  $90^\circ$  from the direction of the wind will produce a piling-up of surface water against one coast of the Red Sea, such a piling-up being, to some extent, balanced by a bottom current in the opposite direction; thus a combination of water movements will tend to produce a solenoid field in the sense of Bjerknes (Bjerknes, 1911; Bjerknes and Sandström, 1910), causing movement of the water mass in the direction of the wind.

The net results, then, of a wind blowing from NNW. down the Red Sea should be:

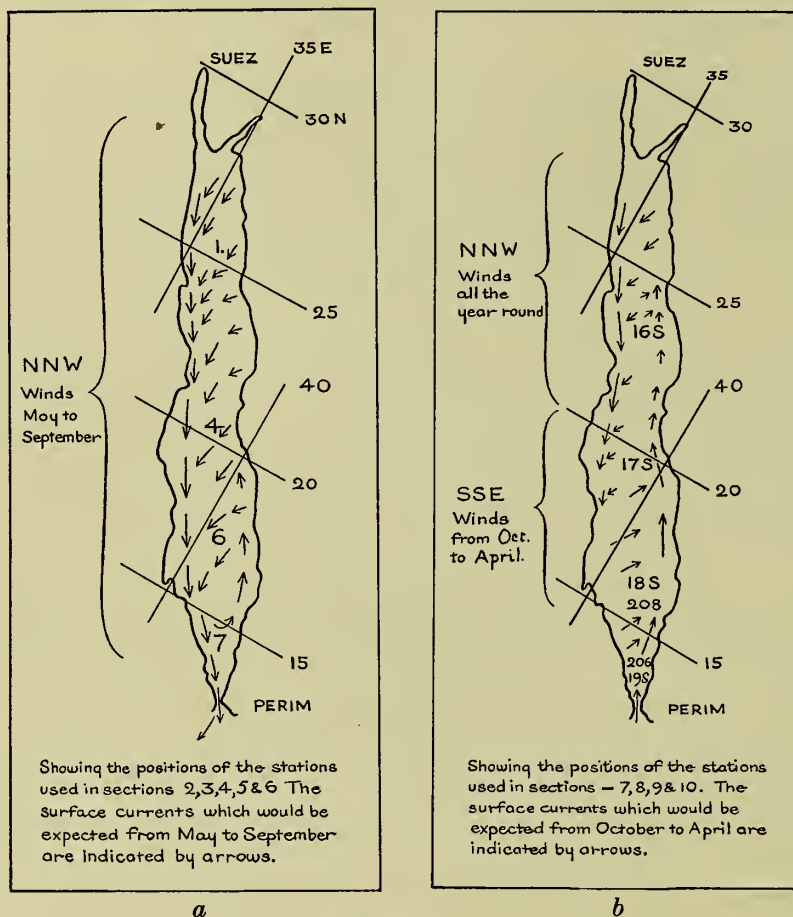
(1) A clockwise circulation in a vertical plane at right angles to the direction of the wind, with a piling-up of surface water on the African coast and an upwelling of deeper water moving in an easterly direction with a more or less stationary "cell" between these two movements (*cf.* Sverdrup, 1938).

(2) A movement of water, most pronounced in the surface layers, in the direction of the wind (*i.e.* parallel to the coast), this movement being the combined effect of the component of the pure wind current in this direction, the accumulation of surface water against the coast, and the extent to which the Coriolis force is overcome by frictional forces.

For the SSE. wind, blowing up the Red Sea, the phenomena will be exactly the same, but the direction of transport and trajectory will be in the opposite direction.

From this discussion it can be seen that for half the year, from May to September, the wind system will produce a clockwise circulation in a vertical plane at right angles to the direction of the wind, light surface water being transported to the Egyptian or western shore, and deep heavy water tending to well up on the Arabian or eastern shore.

At the same time there will be a movement, chiefly confined to the surface layers, in the direction of the wind, that is towards the Straits of Bab-el-Mandeb, and thus a current of surface water flowing out of the Red Sea. But the exit from the Red Sea is narrow and shallow, so that surface water will be piled-up in the southern end of the Red Sea, just north of these straits. This piling-up of surface water will produce a sinking of surface water at the place where it accumulates, together with a corresponding upward movement of deep water in the northern part of the Red Sea, from which the surface water has been removed. The surface currents to be expected in this season of the year are shown in Text-fig. 1, *a*.



TEXT-FIG. 1.

For the second half of the year, from October to April, the wind current system in the area north of 22° N. should be exactly the same as that described above; but south of about latitude 20° N. the wind system is completely reversed, so that in this region the opposite effect is produced. In this southern portion the circulation, in a vertical plane at right angles to the wind's direction, will be in the opposite direction from that of the previous season. The movement of water in the direction of the wind will now be towards the NNW. with a piling up of the light surface water along the Arabian or eastern coast, and a clockwise movement of the deeper masses, with upwelling along the Egyptian side. At about 20° N. latitude there will thus be a tendency for two circulations in the vertical



plane at right angles to the long axis of the sea, to rotate in opposite directions; while surface water will be driven both from the north and from near the Straits of Bab-el-Mandeb and will pile up near this latitude. This will produce a sinking of surface water near this spot and a compensating upward movement just north of the "Sill".

According to the relative strength of the north- and south-going currents, along the west and east coast respectively, there will be a greater or less area of overlap at about  $22^{\circ}$ – $25^{\circ}$  N. latitude, in which both the north and south and east and west currents may be expected to appear. The surface currents to be expected in this season are shown in Text-fig. 1, *b*.

The current entering the Red Sea from the narrows at Bab-el-Mandeb during the winter months is sufficiently rapid to have at least some of the characteristics of a Wake Stream, and will therefore, according to the conclusions of Rossby (1936), produce counter-currents consisting largely of anticyclonic eddies. The data at present available is not sufficient for a discussion of this aspect, but the erratic nature of the navigational records suggests that such a phenomenon is present.

From Vercelli's data (1930) it can be seen that in the extreme north of the Red Sea the surface water is cooled from September onwards, till the minimum temperature is reached in February ( $18.1^{\circ}$  C.). As we move south, the average annual temperature change, both of the air and the surface water, decreases rapidly. Such a state of affairs will greatly increase the density of the surface water in the most northern part of the Red Sea (by  $1.76 \sigma_t$  units). As the corresponding change in the southern portion is only about  $0.46 \sigma_t$  units, it is to be expected that there will be a steady sinking of surface and subsurface water in the extreme north during the winter season. This effect will begin in late September, but will not reach its maximum effect till February, and will not seriously slacken till June. It is important to realize that this season of sinking does not entirely coincide with the winter wind season. Such a sinking will have to be compensated by movements from the south, for the rainfall is negligible. This compensating flow probably occurs chiefly along the Arabian coast.

Such, then, is the circulation which, on theoretical grounds, would be anticipated; each system will have reached its maximum development at the beginning of the opposite season, *i.e.* in October and May.

It will be realized that the longitudinal water movements in the Red Sea, piling up surface water near the Southern Sill in summer, and near latitude  $21^{\circ}$  N. in the winter, will produce high sea surfaces at these points in their respective seasons, and such elevations will appear in the dynamic picture of the surface. It is obvious, however, from the nature of the forces producing these surface deformities that Bjerknes' circulation theorem cannot be applied to these longitudinal sections. In fact, movements as calculated from dynamic topography will in many cases be exactly opposite to those actually known to occur from navigational observations.

#### CONSIDERATION OF DATA.

The data used in the construction of the following sections has been taken from the results of the John Murray Expedition (1933–34) and the "Snellius" Expedition (1929) (Van Riel, 1932). Curves have been drawn for the distribution with depth of salinity,



temperature, oxygen and density, and for the salinity-temperature correlation. The curves have been somewhat smoothed by reference to the density curves according to the procedure of Helland-Hansen (1916) and Helland-Hansen and Nansen (1926), and the figures for the sections have been taken from the smoothed curves.

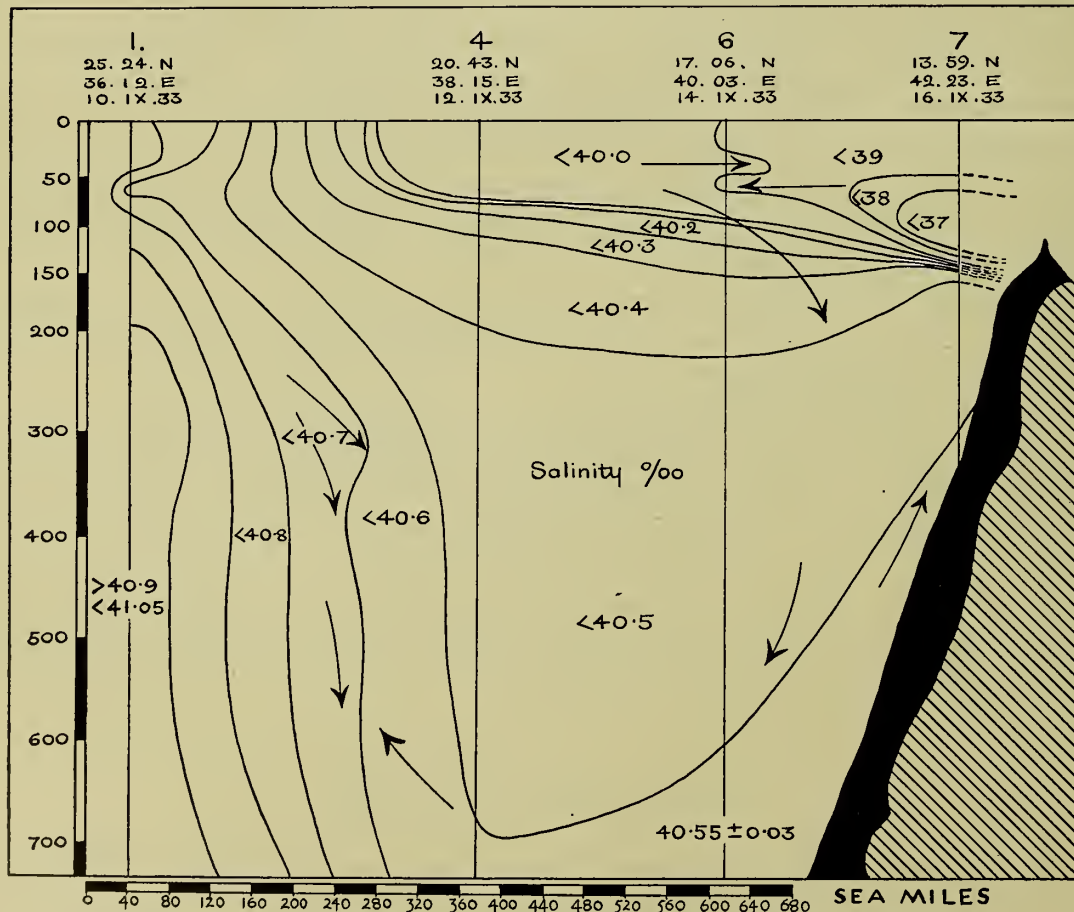
It should be pointed out that the stations used are several hundred miles apart and that the vertical scale is about 1800 times as large as the horizontal one.

Stabilities are usually quoted as  $\frac{\Delta\sigma_t}{\Delta \text{ depth}} \cdot 10^3$ .

## RED SEA AT THE END OF THE SUMMER SEASON (MAY TO SEPTEMBER).

### THE DISTRIBUTION OF SALINITY IN SEPTEMBER.

In Text-fig. 2 at Station 1 the southward bend of the isohalines down to 30 metres indicates the movement of high salinity surface water from the northern portion of the region under the influence of the NNW. wind. The depth to which active wind transport is indicated agrees well with the depth at which maximum stability is found (35 metres). This movement is possible owing to the summer warming of this saline water, which is consequently relatively light. To understand this sudden bend in the opposite direction at about 50 metres it is necessary to realize that just south of Station 1 the movements



TEXT-FIG. 2.

across the sea are here opposed to one another. Below 50 metres the highly saline water which sank in February and March is seen; by now the sinking is at a minimum.

At Station 4 the salinity down to about 40 metres, the depth at which the discontinuity is found, indicates the approximate depth of active wind produced movements. Below 40 metres the steep density discontinuity is characterized by a rapid rise in salinity to about 80 metres. This depth represents the level to which active mixing can take place in the winter months, when owing to the cooling of the surface layer the discontinuity had sunk to this level. Below 80 metres, the salinity increases more slowly, so that the 40.4 isohaline is found at 180 metres and water with a salinity of over 40.5 ‰ at 700 metres. Below this depth to the bottom the salinity change is so small, 0.03 ‰, that it seems unprofitable to discuss it here.

The surface water at Station 6 consists of water with a salinity <39 ‰. This is largely a relic of the surface water driven into the Red Sea from the Gulf of Aden by the winter winds, though perhaps a small portion of it may be derived from the deeper Gulf of Aden Stream. Below this surface layer the arrangement of the isohalines is quite comparable with those at Station 4, but here the sinking, which was predicted on theoretical grounds, is indicated by the consistently lower level of all the isohalines above 40.3 ‰.

At Station 7 the water down to 40 metres is continuous with the surface water at Station 6; but below this level we see a much less saline body of water with a nucleus of salinity <37 ‰. This low salinity water, inserted between water masses of much higher salinity, is coming in from the Gulf of Aden as a current to compensate for the surface loss from the Red Sea. The upper boundary of this low salinity water in 40–50

metres is characterized by an extraordinarily high stability, the value of  $\frac{\Delta\sigma_t}{\Delta \text{depth}} \cdot 10^3$  being 160. It would seem impossible for much vertical mixing to take place across this extremely sharp discontinuity, and we must assume the major part of the assimilation takes place by horizontal mixing.

In general the section shows the outflow of Red Sea surface water over the “Sill”. The piling up of Red Sea surface water at Station 6 with a resultant down-pushing of the lower layers is well indicated. It is worthy of note that the downward component seems to be most marked between Stations 6 and 7, and this is probably due to the fact that the inflowing Gulf of Aden water really acts as a barrier additional to the “Sill”. The upturning of the 40.5 isohaline, which rises to 270 metres at the barrier, is probably due to the fact that the piling-up does not occur actually at the “Sill”. No doubt there is a slow creep of the deep Red Sea water up the slope to the “Sill”.

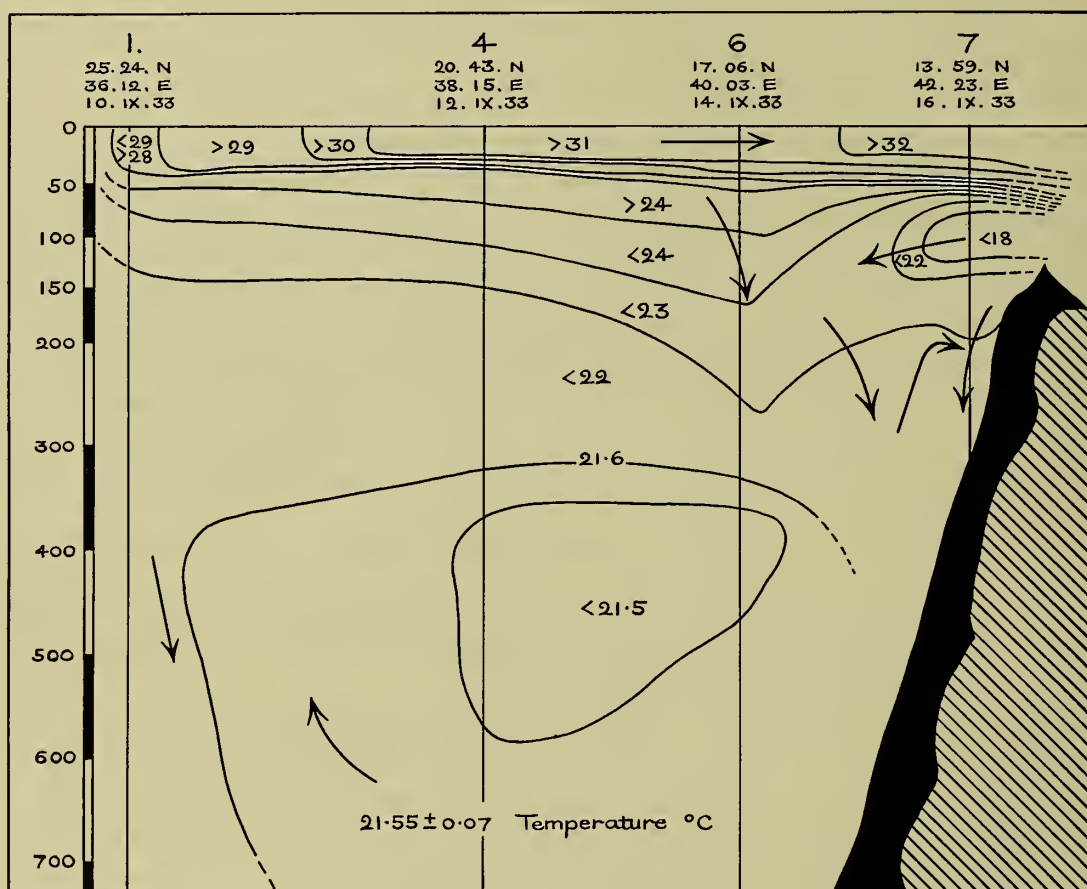
#### THE DISTRIBUTION OF TEMPERATURE IN SEPTEMBER.

At Station 1 there is a fairly steep fall till 22° C. is reached at about 130 metres. Below this level the temperature falls very slightly to a minimum of 21.61° C. at 400, and then rises slowly to 21.84° C. at 1900 metres. The secondary rise is largely, though not entirely due to adiabatic heatings. This relatively low temperature (about 22° C.), together with the very high salinity (>40 ‰) clearly indicates the origin of this water. From the salinity it must have originated at the surface in the north of the Red Sea; and from its low temperature it must have come from north of 26° N. latitude and have sunk during the months of February–April.



The temperature distribution at Station 4 requires little comment. It shows quite clearly the depth to which the wind current extends (about 40 metres). The subsequent slow rate of fall, the minimum at 400 metres and the great constancy of temperature below 150 metres are in complete agreement with the suggestions offered in the discussion of the salinity section.

At Station 6 a very marked down-bending of the lines occurs, so that the  $22^{\circ}$  isotherm is not reached till about 240 metres. This sinking of the lines of equal temperature indicates quite clearly an accumulation of surface water in the region, in good agreement



TEXT-FIG. 3.

with the isohalines of the previous section. At 400 metres a minimum ( $21.42^{\circ}$  C.) is reached, but below 500 metres the same constant temperature is found as at Station 4.

Station 7 shows a further increase of surface temperature, while the upper boundary of the surface current is clearly indicated by the crowding of the isotherms between 40 and 60 metres. The inflow of subsurface Gulf of Aden water is clearly marked by a tongue of low temperature water, the nucleus of which, at about 70 metres, has a temperature below  $18^{\circ}$  C. Lower down the secondary rise of temperature indicates where we have again entered water of Red Sea origin.

In general the section shows the same phenomena as were seen in the salinity section. There is strong indication of a piling-up and a consequent downward tendency of surface water between Stations 6 and 7. The intermediate temperature minimum at Station 7

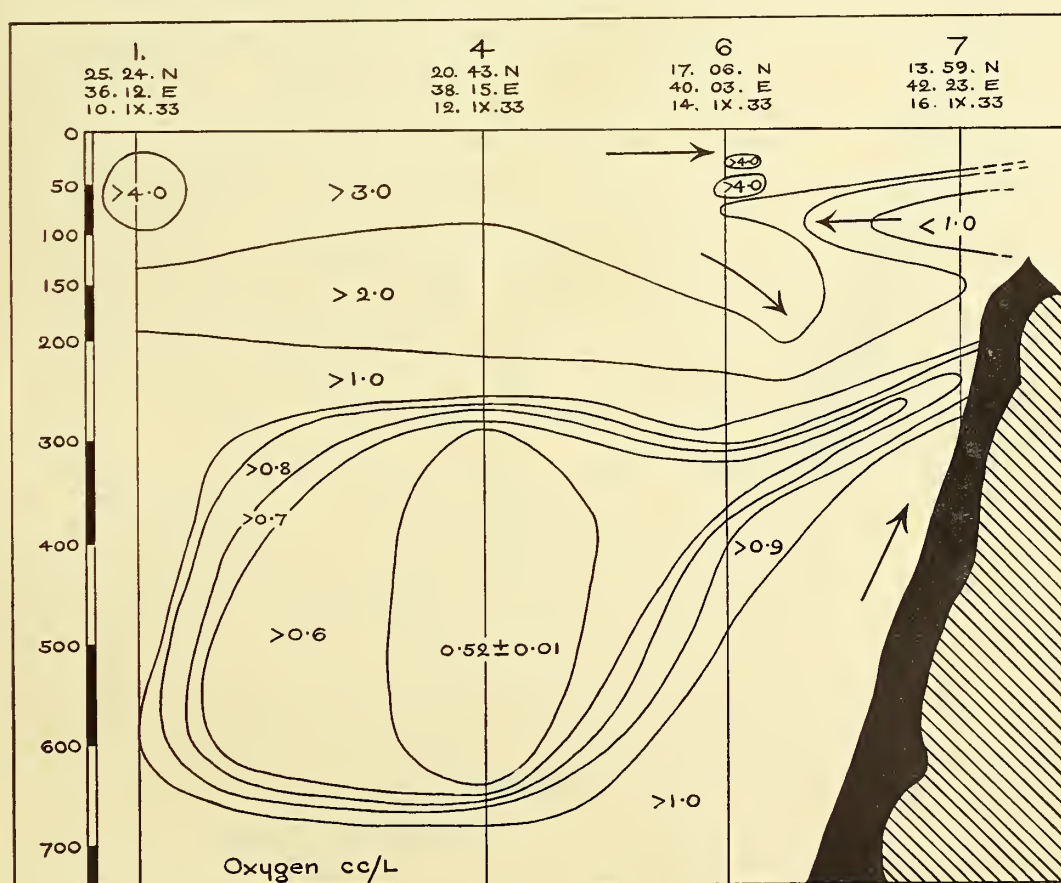


is additional evidence of the existence of an influx of cold, low salinity water from the Gulf of Aden, below the warm high salinity outflow. The upward bend of the 22° C. isotherm between Stations 6 and 7 strongly suggests that there is at least some upward movement of the deep Red Sea water from the depths between the down-welling and the "Sill". The extraordinary constancy of the temperature below about 300 metres is quite in agreement with the very constant salinity found at all depths below this level. It emphasizes the fact that the sinking of the water in the northern part of the Red Sea can occur only during a very limited period, and suggests that the sinking is accompanied by considerable turbulence, producing complete mixing. A reference to the density section shows that this is in complete agreement with the modern view (Parr, 1938) that mixing occurs chiefly along the isosteric surfaces and not across them.

#### THE DISTRIBUTION OF OXYGEN IN SEPTEMBER.

At Station 1 the surface oxygen shows little significant variation down to nearly 100 metres; from there it falls rapidly to 3 c.c./l at 130 metres, 2 c.c./l at 190 metres, with a minimum of 1.0 c.c./l at 600 metres. From here there is a rapid though somewhat irregular rise, till at 1900 metres the oxygen content is 2.07 c.c./l.

At Station 4 the surface water has a concentration of up to 3.99 c.c./l, falling to 3 c.c./l at 90 metres and 2 c.c./l at about 200 metres. From here on the distribution with



TEXT-FIG. 4.

depth falls very rapidly, so that at 300 metres it is only 0.53 c.c./l, and remains at this low value to below 600 metres. Below this depth the concentration rises rapidly to 2.04 c.c./l at 1500 metres.

Station 6 shows relatively high oxygen. The distribution shows considerable irregularity, which can no doubt be attributed to the fact that at this point there are two currents with very different characters moving in opposite directions. At this station there is a small portion of less than 3 c.c./l at 80 metres, which seems to be due to the effect of the Gulf of Aden stream. Apart from this small portion the concentration remains above 3 c.c./l till below 150 metres, and the 2 c.c./l line is not found till 230 metres, or 30 metres lower than at Station 4. When it is borne in mind that at this point the water is met by the Gulf of Aden stream the nucleus of which has an oxygen concentration of less than 0.6 c.c./l it is seen that the down-welling of the surface water must be a very well-defined movement. Below 250 metres the concentration drops rapidly to a minimum of 0.60 c.c./l at 300 metres. Thence it rises rapidly to 2.18 c.c./l at 800 metres, only to fall again to 1.09 c.c./l at 1000 metres.

At Station 7 we find surface water with a concentration over 3 c.c./l down to 40 metres. Thence it drops rapidly to a minimum of 0.57 c.c./l at 100 metres. Below this it rises rapidly to 2.12 c.c./l at 150 metres to fall again to 0.75 c.c./l at 250 metres.

The diagrams as a whole show the same evidence for a downward component between Stations 6 and 7, as was seen in the salinity and temperature diagrams. The minimum oxygen zone between 300 and 600 metres at Station 4 agrees well with the position of the temperature minimum; and here, again, the thinning out of the minimum oxygen zone in between Stations 6 and 7, and the upward curve of the lower 1 c.c./l line against the barrier indicates the same slight upward movement of deep water between the piling-up of surface water and the barrier, as was seen in the other two sections.

Except at Stations 6 and 7, the boundary of the wind-driven current is not well marked. This is due to a combination of physical and biological processes. In these clear waters Gilson (1937) has shown that active photosynthesis can continue down to about 160 metres, so that production of oxygen from this source would tend to obscure the depth of active surface mixing which must be confined to much shallower levels. The physical reason is to be found in the piling-up of surface water in this region (between Stations 1 and 4) during the winter months, the effect of which on the oxygen concentration is seen well below 150 metres.

The secondary rise of oxygen values at depths below 600 metres strongly suggests that the main mass of high salinity water sinking in winter from the northern end of the Red Sea falls to considerable depths relatively rapidly; and that the low oxygen values at 350–550 metres represent a "cell", fed only very slowly by water from greater depths.

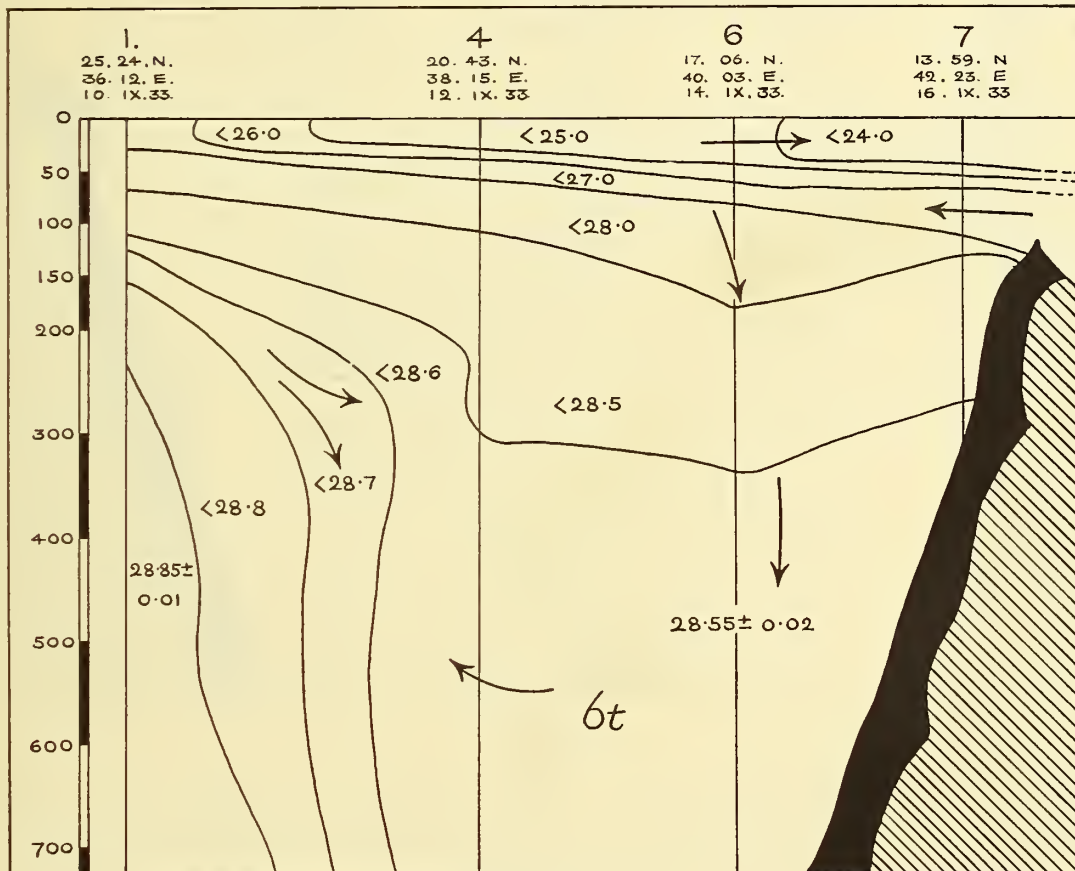
The subsurface inward movement of water from the Gulf of Aden, seen in the previous sections as a tongue with a low salinity and temperature, is here represented by a body of water with a low oxygen value. As it advances into the Red Sea, its concentration of oxygen is increased, chiefly by lateral mixing. The low initial oxygen concentration found in this water is an indication of "age", not stagnation.

#### THE DISTRIBUTION OF DENSITY IN SEPTEMBER.

The distribution of density in this season supports much that has already been said in discussing the other sections. The bending of the isosteres below 100 metres between

Stations 4 and 1 indicates where the deeper dense water is overlaid by surface water from the eastern (Arabian) coast. The accumulation of surface water in the region of Station 6 and the tendency for water from the deeper layers to creep up immediately against the "Sill" are clearly seen in the course of the 28.0 and 28.5 isosteres.

At Station 1 density rises slowly to 28.86. If no allowance is made for adiabatic warming, there is a secondary minimum at 1900 metres, but when this allowance is made (Hesselberg and Sverdrup, 1914) and potential densities are used, this minimum disappears. The whole of the water south of Station 4 and below 300 metres shows very small positive or zero stability, and at about 400 metres at Stations 4 and 6 very small negative stabilities



TEXT-FIG. 5.

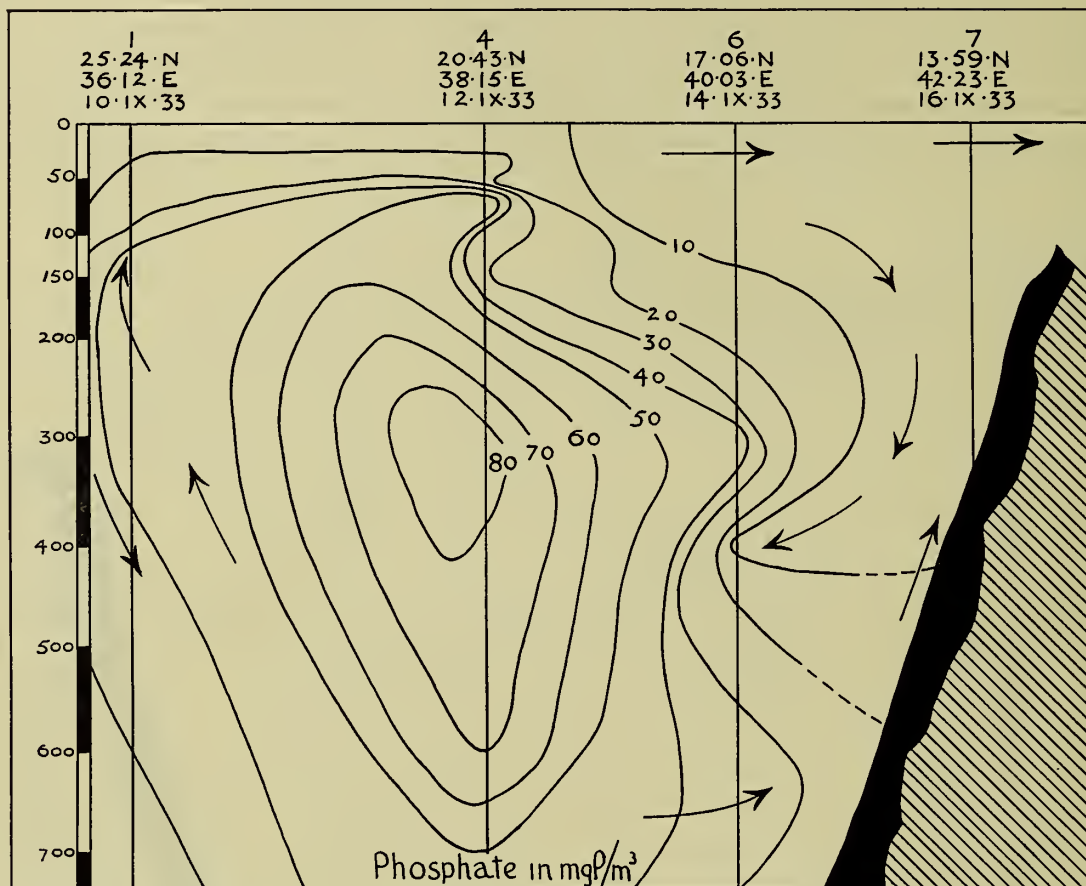
are found. The low stability in the deeper layers probably contribute largely to the great homogeneity of the deep bottom water.

#### THE DISTRIBUTION OF PHOSPHATE (MG.P/M<sup>3</sup>) IN SEPTEMBER.

There seems little need to describe the Stations in detail. In general Text-fig. 6 shows the same main features as the other sections. The steep downward sweep of the 10 mg. line is a very good indication of down-sinking from the surface of water which has been depleted of phosphate. At about 400 metres it shows a sudden in-turning suggestive of a circular movement in a clockwise direction, with the 80-mg. portion as the centre of the rotation. This 80 mg. part, the maximum value found, is at the same



position as the centre of the oxygen and temperature minima. Low oxygen, accompanied by high phosphate, is usually an indication of water which has for a long time been cut off from the surface and has not undergone any great mixing with other waters. As will be seen later, this is the case here.



TEXT-FIG. 6.

#### RED SEA AT THE END OF THE WINTER SEASON (OCTOBER TO APRIL).

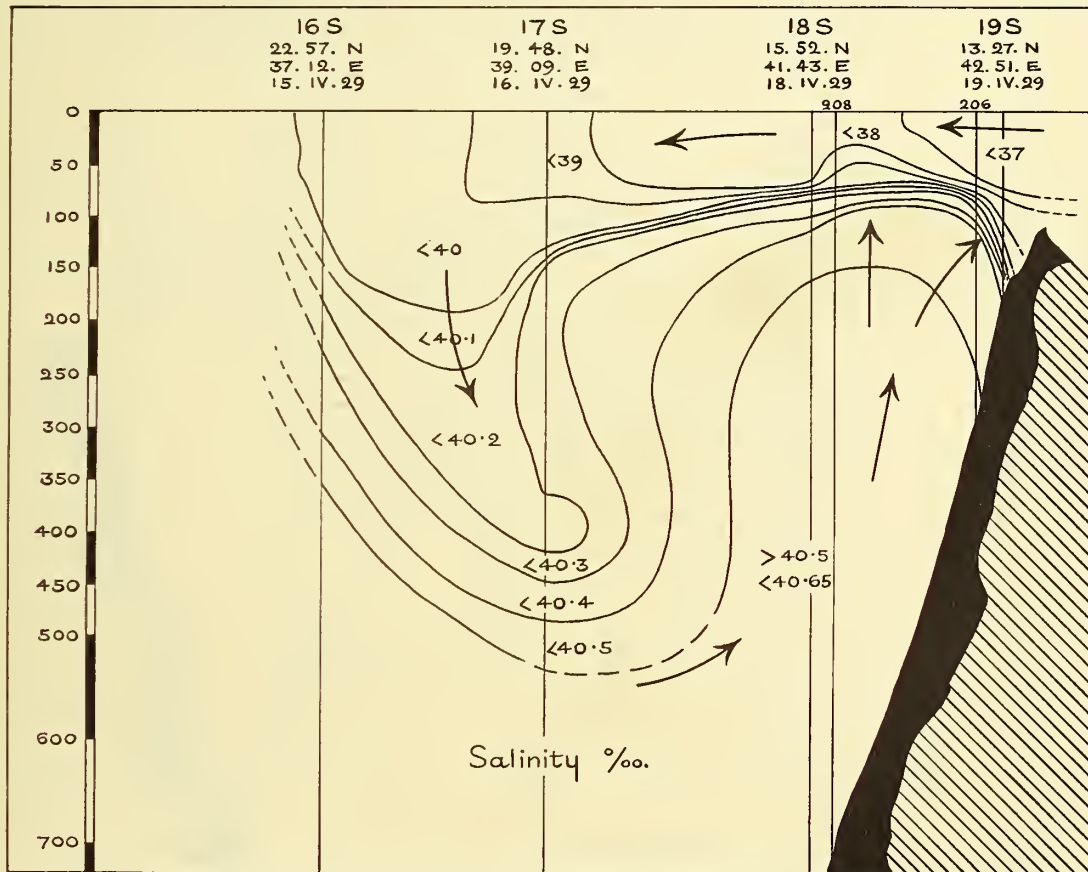
Of the stations used in the following sections, four, 16S, 17S, 18S and 19S, are from the "Snellius" Expedition (Van Riel, 1932), and were carried out in April, 1929. Stations 206 and 208 are from the John Murray Expedition (Sewell, 1936) and were carried out in the middle of May, 1934. It is unfortunate that we have to consider together stations that were carried out at such long intervals, but the paucity of the material is such as to allow of no alternative.

#### THE DISTRIBUTION OF SALINITY IN APRIL AND MAY.

The main features of Text-fig. 7 are fairly obvious. There is clearly an inflow of fairly saline surface water from the Gulf of Aden. Such a current was predicted in view of the SSE. winds prevailing here at this season of the year. Reference to Text-fig. 1, *b* will show that this current transports water chiefly up the Arabian coast to between Stations 17S and 16S, and from there the water is carried across the sea towards the west (African)

shore. The accumulation of this surface water at about latitude  $21^{\circ}$  N. is clearly indicated by the trend of the isohalines in this position. The great depth to which this surface water affects the isohalines is probably to be explained by the low stability ruling in this region at this time of the year (Text-fig. 11), a condition which favours vertical mixing.

Such an accumulation of surface water, with its consequent pressure on the lower layers, must cause an equivalent upward movement of the deep water at some other locality. As this is the season when the very saline water from the extreme north is sinking to great depths, an upward movement of deep water cannot take place there.



TEXT-FIG. 7.

It must occur near the "Sill" at the southern end of the Sea. That this is so is indicated by the lines marking off the water of salinity  $>39\text{‰}$  in the region next the "Sill". This interpretation is also supported by the salinity-temperature correlations. From the raised positions of the high salinity water next the "Sill" as compared with the condition in the summer season, it may be inferred that there is a far greater outflow of this deep Red Sea water at this time of year than in the previous season.

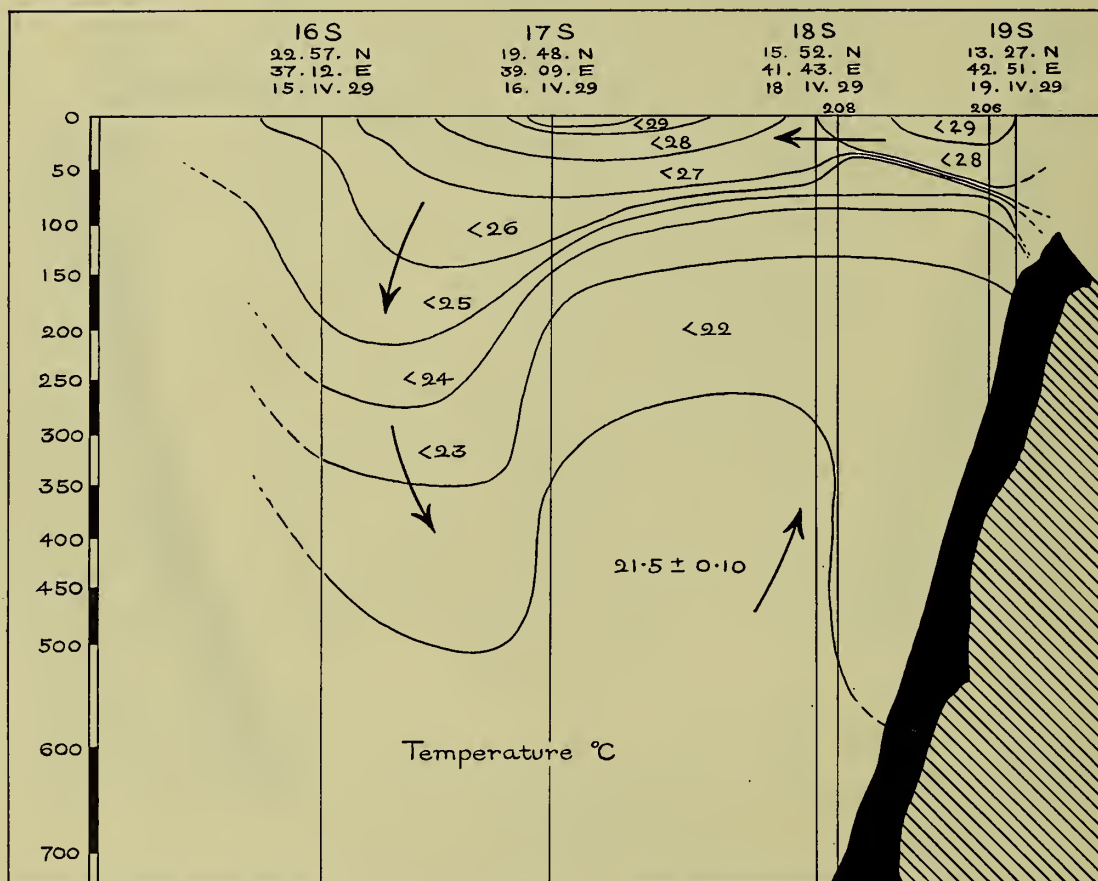
It is difficult to determine the depth of this inflowing surface current in the southern part of the sea. Reference to the stability curves (Text-fig. 11) shows that there is rather poor agreement between the "Snellius" and John Murray stations. This may be due to the difference in the years of observation, or perhaps to the internal waves known to occur in this region (Vercelli, 1927-1930; Schott, 1929). It may be estimated that the depth

of the inward movement in the region of Station 18S is about 80 metres. It is interesting to note that whereas in the summer the inflow from the Gulf of Aden consists of *sub-surface* water, the inflow is now confined to the *surface*, and the position of the summer sub-surface inflow is occupied by a highly saline bottom outflow.

The sinking of high salinity water from the north is indicated by the asymmetrical nature of the curves between Stations 16S and 17S.

#### THE DISTRIBUTION OF TEMPERATURE IN APRIL AND MAY.

Reference to Text-fig. 8 shows good indication of the wind-driven surface current entering from the Gulf of Aden and the piling-up of surface water at about 20° N. The



TEXT-FIG. 8.

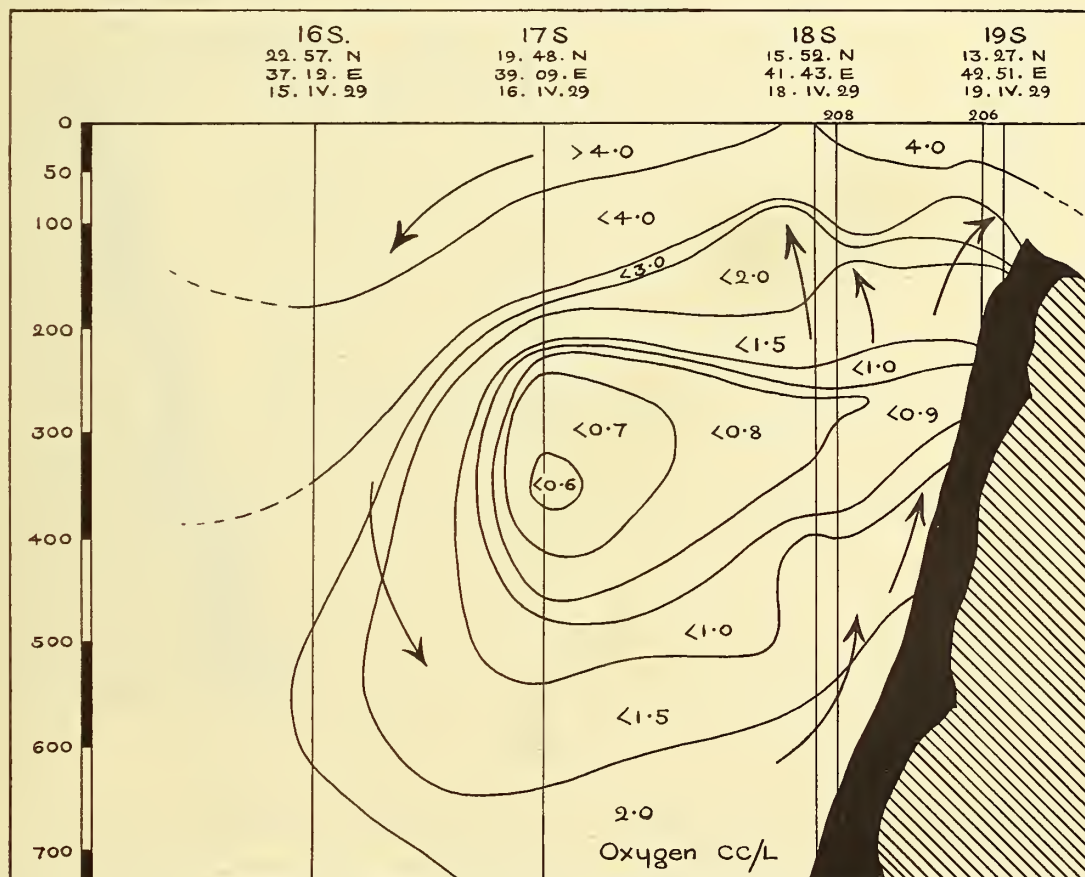
downward mixing of water in this region is strongly indicated by the downward bending of the isotherms. At Stations 18S, 208 to 206 and 19S there is also the same indication of an upward movement of deep Red Sea water as was seen in the salinity figure. The crowding of the isotherms round 27° between Stations 208 and 206 strongly supports the view that two different and opposed bodies of water are meeting here.

There is a suggestion of an eddy in the region of Station 18S. Such an eddy is to be expected on the left side of a fast-flowing current of this type (*cf.* Rossby, 1936), being part of the resulting counter current, which will consist largely of eddies.



## THE DISTRIBUTION OF OXYGEN IN APRIL AND MAY.

As in the salinity and temperature figures, so here, too, there is good evidence of a wind-driven current bringing in surface water from the Gulf of Aden and piling it up, with the resulting downward mixing in the region of  $20^{\circ}$  N. The low stability of the water here at this time would facilitate this downward mixing. That such a phenomenon occurs is clearly indicated by the sharp downward bending of the isolines. There is likewise indication of an upward movement at Station 19S, and at 206. It would seem that the "upwelling", deep Red Sea water is split by the inflowing Gulf of Aden surface current,



TEXT-FIG. 9.

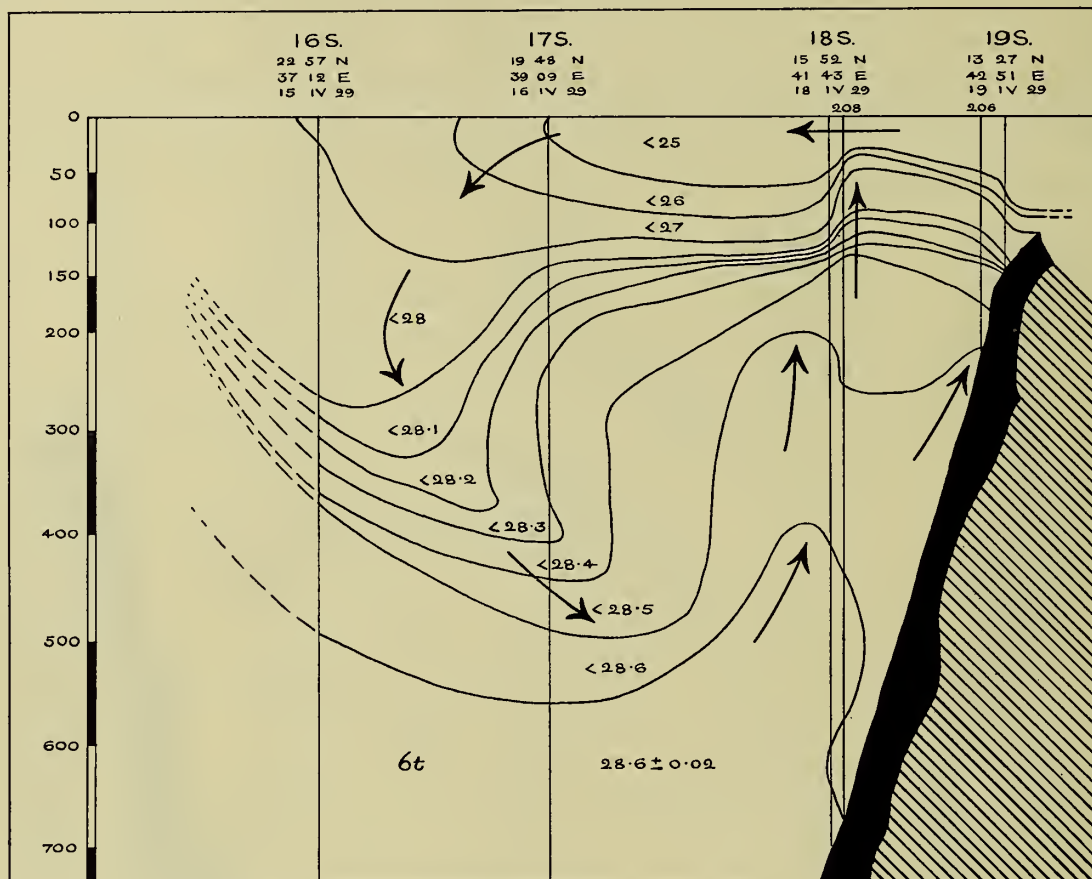
one part appearing at the barrier, the other being carried upwards and backwards and mixing with the surface current at Station 18S. This second portion of deep water, reaching the surface at Stations 18S and 208, is probably centred in the eddy to be expected here.

The relatively high oxygen concentration ( $>2.0$  c.c./l) in the deepest northern waters also suggests that very saline water, coming from the region of the Gulf of Suez, is at this time sinking down and moving slowly southward.

An interesting feature of the figure is the appearance of an oxygen minimum, centred at Station 17S at about 350 metres. The recurrence of this phenomenon in approximately the same place as was found for the previous season is significant.

## THE DISTRIBUTION OF DENSITY IN APRIL AND MAY.

Here, again (Text-fig. 10), we find unmistakable signs of surface inflow from the Gulf of Aden, piling up and mixing with the lower layers in the region of  $20^{\circ}$  N., and of an upward tendency of deep water both toward Station 18S and near the "Sill".

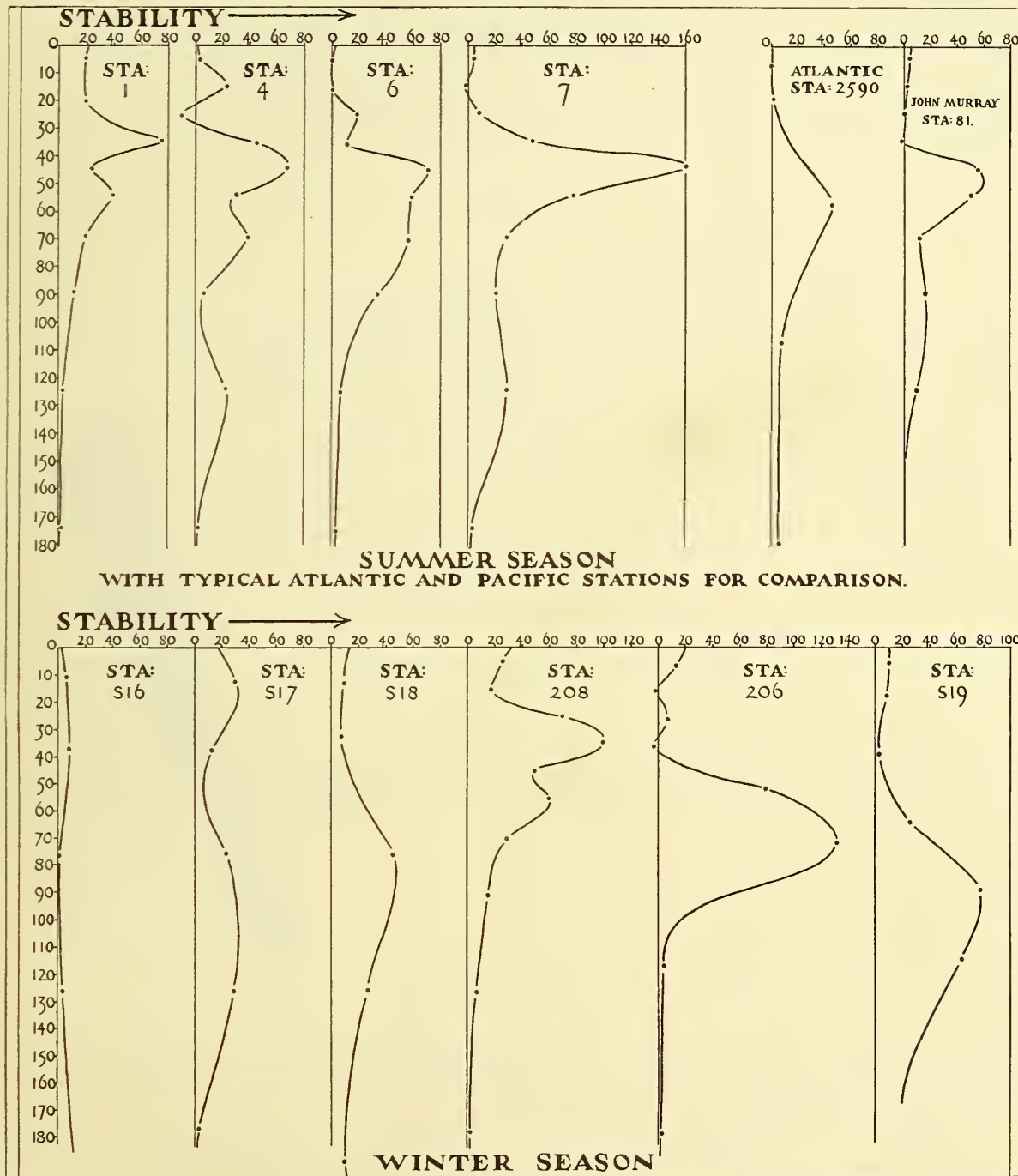


TEXT-FIG. 10.

## THE DISTRIBUTION OF DENSITY IN THE WINTER AND SUMMER SEASONS.

Text-fig. 12 is merely a combination of Text-figs. 10 and 5. It shows quite clearly how, in the winter season, there is a piling-up of surface water and consequent downward mixing in the region of  $20^{\circ}$  N. latitude, with resulting upward movements near the barrier, whereas in the summer season the reverse is the case. The whole system appears to be pivoted about the position X on the figure. In this interpretation we find the explanation of the oxygen-poor, phosphate-rich water, already seen, for X is almost exactly the centre of this region. It is seen, then, that this central region of water is a pivot, on which the rest of the sea rotates in a vertical plane, so that as one looks at the figure the rotation is anti-clockwise in the winter, clockwise in the summer. This pivotal region is very nearly permanent in position. It is exposed but little to mixing and consequently has little opportunity for renewal of oxygen, or loss of phosphate. As a result, the former has been largely used up and the latter has greatly accumulated. By close examination of the salinity-temperature and salinity-oxygen correlations it can be shown that this cell,

forming the pivot mass, is not absolutely cut off from outside supplies and mixing. During the winter it receives a supply of water of considerably higher oxygen concentration,

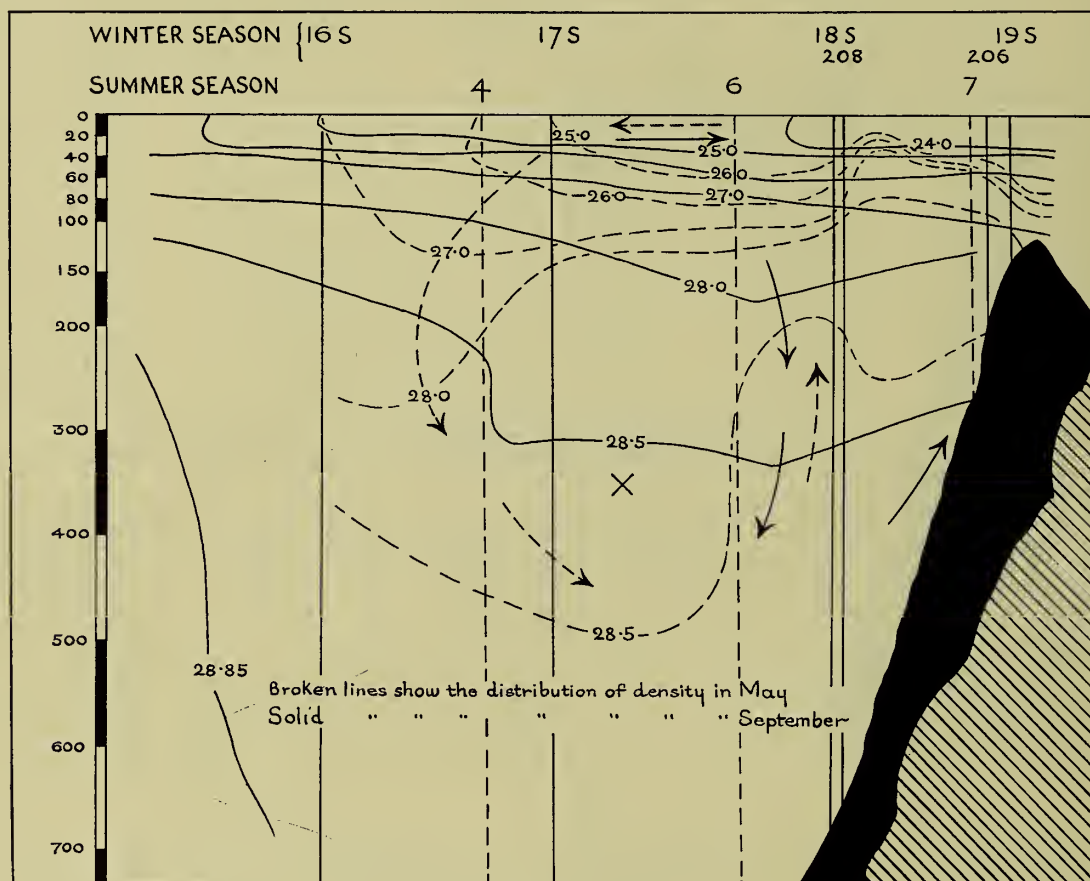


TEXT-FIG. 11.

slightly higher temperature and rather lower salinity. The nature of the movements by which this cell is fed are not at present clear, but there is a suggestion that they are largely confined to the winter season and are, at least to some extent, dependent on seasonal changes in the circulation *across* the sea.



There is a slow sinking of very saline water from the north end of the Red Sea. The fundamental assumption that all waters have had their origin at the surface, or from mixtures of surface waters, leaves no other source for the water of salinity  $>40.0\text{‰}$  and a temperature of  $22 \pm 0.5^\circ \text{C}$ ., which fills practically the whole Red Sea basin below 180 metres and is the most characteristic feature of the zone. As the original surface water must have had a temperature not much greater than  $22^\circ \text{C}$ ., it is obvious from Vercelli's data (1930) that the sinking must occur from February to April and from north of  $26^\circ \text{N}$ . latitude. This is in entire agreement with the figures of the sections, and with the density



TEXT-FIG. 12.

changes required by such a sinking. The longitudinal rotational movements are such that there will tend to be a far greater escape of this deep, highly saline water over the "Sill" in the winter than in the summer.

Additional confirmation of the vertical rotational movements in the northwest-southeast direction can be obtained from a consideration of the salinity-temperature correlations and their associated oxygen values. From these it can be seen that waters with the same T/S correlations as are found at 420 and 480 metres at Station 16S are found again at Station 18S at 250 and 350 metres respectively. Further, if the oxygen concentrations of these bodies of water with identical conservative characters (T/S) are compared, it is found that the values at Station 18S are about 1.1 c.c./l lower than at Station 16S. It seems reasonable that this lowering of the oxygen values, in passing from

north to south, can have taken place only by this deep water moving in that direction, for alteration due to internal mixing is ruled out by the constancy of the T/S correlations. The rise in the level of the water in passing from Station 16S to 18S is best explained on the rotational theory already stated. The movement of the water from Station 16S to Station 18S with the accompanying consumption of 1.1 c.c. O<sub>2</sub>/l would then occur during the winter season (seven months).

In the opposite season (summer) the oxygen gradient for deep water masses between Stations 6 and 4 is reversed, supporting the conception of a reversal in the direction of rotation with the two seasons. The rate of oxygen consumption is of about the same magnitude as for the winter season.

The writer is not aware of any data on oxygen consumption at such levels (350–600 metres) in water with such a relatively high temperature (*circa* 22° C.). From the data available for the rate of oxygen consumption in the Atlantic it would seem not unreasonable to assume a consumption here of 2 c.c./l/year. This would agree with the suggested circulation and the results from the T/S correlations, which suggested that water moved from 420 metres at Station 16S to 250 metres at Station 18S in seven months during the winter, moving back again during the five months of the summer season. This would give the water at about 400 metres, south of 23° N. latitude, a winter velocity of slightly less than 2 miles per day, or 3.7 cm./sec., towards the SSE., and a summer velocity of slightly more than 2 miles per day in the opposite direction. Such a rate of flow is quite comparable with the rates of flow usually found under similar conditions.

Superimposed on this system are the rotational movements towards the Arabian and African coasts in a plane at right angles to the long axis of the sea, due to the *cum sole* component of the seasonal winds. In the northern part of the sea the movements have the same direction throughout the year, but south of latitude 22° N. there is a reversal with the change of season.

These conclusions are in complete agreement with all the data at present available. That such a simple circulation has not been previously elucidated is probably due to the fact that up to the time of the John Murray Expedition, satisfactory data for the summer season were not in existence.

### SUMMARY.

1. The physical conditions of the area are analysed and the probable circulation to be expected is deduced. The hydrographic data are then discussed and shown to agree with the predicted circulation.

2. It is shown that the whole of the Red Sea below a depth of 200 metres is filled with water of extraordinarily constant temperature and salinity. From the properties of this water it is seen that it must originate at the surface in the Red Sea, north of latitude 26° N., and sink from there between late January and early April.

3. The upper layers of the sea are subject to a wind-system which changes with the two seasons.

In the summer water is transported down the whole length of the Red Sea, to pile-up near the "Sill" in the south and cause an outflow of the "jet" type through the Straits of Bab-el-Mandeb into the Gulf of Aden. Owing to the considerable stability now found here at 40–50 metres, active wind transport is confined to a layer of this depth, and mixing



must be largely horizontal, though vertical mixing will be found at the scene of the upwelling along the Arabian coast.

During the winter the wind system is such that the currents in the Red Sea south of latitude  $20^{\circ}$  N. are reversed, and there is a piling-up of surface water near that latitude. At the scene of this accumulation of surface water there is now relatively little stability in the upper layer, so that considerable vertical mixing can take place; thus the effect of the surface accumulation is now felt to considerable depths. Lateral transport, south of latitude  $20^{\circ}$  N., is now towards the Arabian coast, where surface water accumulates. There will be a corresponding tendency for upwelling on the African coast.

4. The seasonal change in the surface current system tends to cause corresponding rotational movements in both longitudinal and transverse vertical planes. The centre of the longitudinal "vertical" rotation is situated at about 320 metres in  $17^{\circ}$  N. latitude. This centre, characterized by very low oxygen and high phosphate values, seems to be the centre of a fairly permanent "cell". Below the cell, the seasonal winds induce seasonally alternating deep currents with a velocity of about 2 miles/day ( $3.7$  cm./sec.). The oxygen consumption at about 400 metres seems to be of the order of 2 c.c./l/year.

5. It is shown that the seasonal alternations of the surface movements will alter the amount of deep Red Sea water flowing out over the "Sill". The effect is such that the flow is at a minimum in the summer season.

6. During the summer the inflow from the Gulf of Aden is entirely subsurface, while in the winter the inflow is confined to the surface layers.

#### ACKNOWLEDGMENTS.

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CHEMICAL AND PHYSICAL  
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THE EXCHANGE OF WATER BETWEEN THE  
RED SEA AND THE GULF OF ADEN  
OVER THE "SILL"

BY

E. F. THOMPSON. M.Sc.(N.Z.), Ph.D.(CANTAB.)

WITH TEN TEXT-FIGURES



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# CHEMICAL AND PHYSICAL INVESTIGATIONS

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WITH TEN TEXT-FIGURES.

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As was pointed out in a previous paper (Thompson, 1939), the Red Sea "proper" is separated from the Gulf of Aden by a shallow sill near the Hanish Islands. This sill reaches its maximum height at about latitude  $13^{\circ} 41' N.$ , where the depth of water is only 100 metres; the bottom then falls away rapidly to the considerable depths of the Gulf of Aden. Most previous workers have used stations further south in the neighbourhood of Perim; but the depths found by the "Mabahiss" (Sewell, 1936) show quite clearly that the real separation between the Red Sea and the Gulf of Aden occurs, not here, where the channel is narrowest, but in latitude  $13^{\circ} 41' N.$ , where it is shallowest.

A number of investigations of this area have already been carried out. The earliest of these was that of the "Stork", and in 1897 the "Pola" (Luksch, 1901) carried out extensive work here. On this data are based the conclusions of Krummel (1911). These deductions have been severely criticized by Vercelli (1927), and their validity, indeed, seems to be extremely doubtful. More recently very extensive investigations of the currents and physico-chemical properties of the water in this region have come from the "Magnaghi" (Vercelli, 1927 and 1930; Picotti, 1930). All these sets of data agree in showing a surface current flowing into the Red Sea from the Gulf of Aden, and a deep flow of more saline water in the opposite direction. The results of the "Ormonde" have been published by Matthews (1927); and he has given a comparison of these results with those of the "Magnaghi" (Matthews, 1928). These two papers are chiefly concerned with the water on the Gulf of Aden side of the "Sill".

All this work has been summarized by Schott (1929). This author discusses the similarity between the interchange at Gibraltar and here. He points out that the position

of the "Sill" is outside the enclosed sea at Gibraltar and inside here. At Gibraltar there is no complete change of the wind system in the two seasons, while here the wind system goes through a complete seasonal reversal, blowing from the NNW. during the summer and from the SSE. during the winter. He has drawn a section from the Red Sea to the latitude of Aden in which he shows the  $38.0^{\circ}/_{\infty}$  isohaline continuous all the way from the Red Sea to the top of the Gulf of Aden. He points out that, though the upper end of the Gulf is, probably, in the deepest layers normally filled with water of a salinity  $>37^{\circ}/_{\infty}$ , there is "good reason" for supposing that water of a salinity  $>38^{\circ}/_{\infty}$  must be only a temporary phenomenon, perhaps due to an intermittent flow from the Red Sea. He also states that the reversal of the winds is such that in the summer months, when the need for replacement of water lost by evaporation in the Red Sea is greatest, the wind system would tend to oppose the compensating inward flow. Of this anomaly he offers no explanation. In view of our previous ignorance of the nature of the exchange here, Schott's work (1929) was a real contribution to our knowledge of these conditions. Unfortunately the paucity of available data forced him to consider stations from widely different times and seasons in the same section. As will be seen from the present paper, this is inadmissible here. Most of the points left by Schott as "undetermined" can be explained when the distinct nature of the exchange in the two seasons is realized.

The most valuable previous work is that of Vercelli (1927 and 1930) on the tide-induced internal waves at the boundary between the inflowing surface and outflowing deep water ("neutral level" of Vercelli). He has shown that they are such that, at the "neutral level", the salinity increases with the flood tide, flowing into the Red Sea, and decreases with the ebb tide. The temperature shows a correlated variation. An explanation of these thermohaline oscillations, dependent on the rhythm of the tide and tide currents, is probably to be found in the explanation already suggested by Schott (1928) for the very similar oscillations in the Straits of Gibraltar. The average winds in these straits have already been described (Thompson 1939) : from October to April they are southerly, and from May to September, northerly. In the deep water of the Red Sea a considerable lag in the change-over of the current system was to be expected, so that the maximum effect of each season was to be found in the early stages of the succeeding one. In these straits the water is comparatively shallow, so that the lag will be less, and an ideal time for examining the complete result of each season would be just at the end of that season, *i. e.* in September and April.

#### CONSIDERATION OF DATA.

The treatment of the data, preparatory to its use in the construction of the following sections, is similar to that previously described (Thompson, 1939).

The material considered in the present discussion consists of five stations carried out by the John Murray Expedition in September (Nos. 6, 7, 8, 9, 13), and repeated in May (Nos. 208, 206, 204, 203, 201). It will be seen that the former series of observations are almost at the ideal time, while the latter, being about a month late, will tend to be confused by the effect of the succeeding season. In each case, so as not to crowd the sections, the first and last stations in each series have been omitted; but they have been used in the extrapolation from the middle three stations. The positions of the ten stations are shown in Text-fig. 1. In the sections the vertical scale is 185 times as large as the horizontal

scale, the distance from Station 7 to Station 9 (or Station 206 to 203) being about 25 sea miles.



TEXT-FIG. 1.

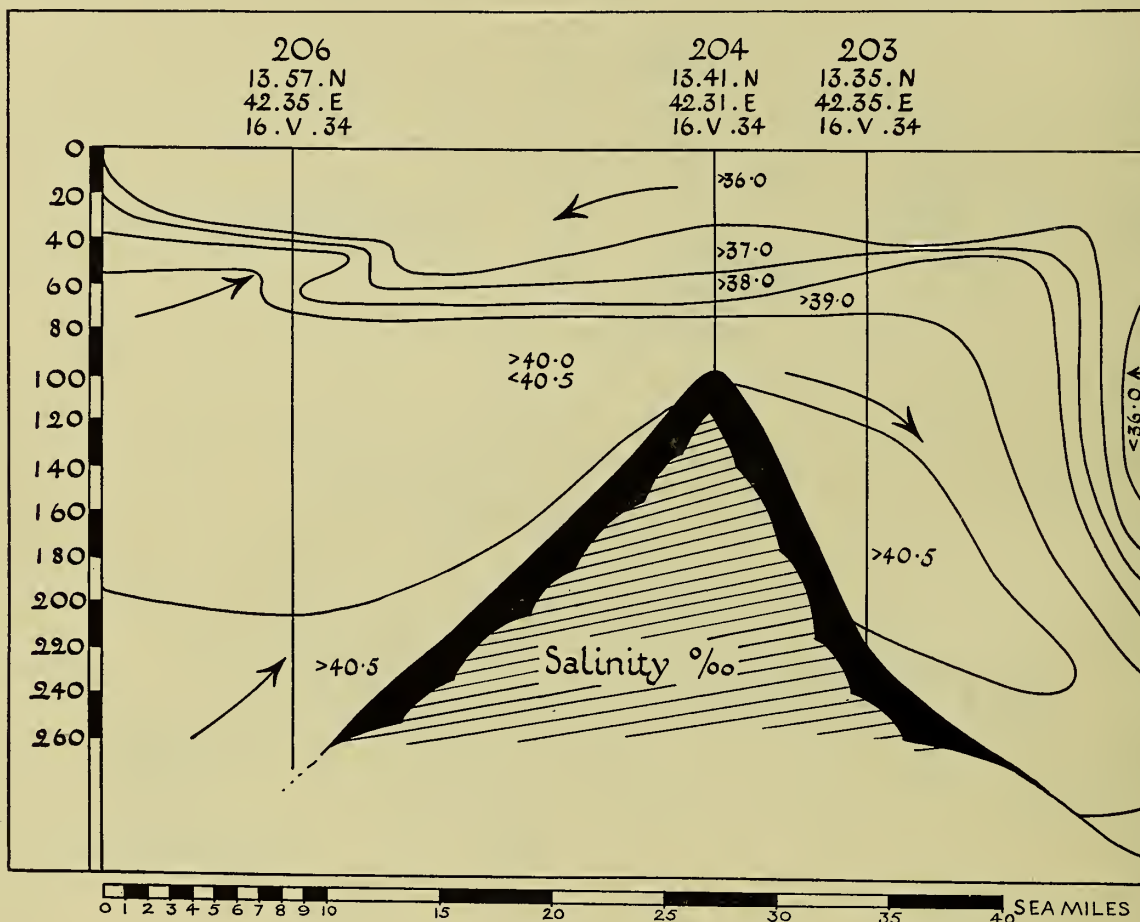
Arrows are used to indicate the direction of transport during the particular season ; and while the actual trajectories during the season will largely coincide with these, at the ends of these seasons the movements will be at a minimum.



## THE EXCHANGE AT THE END OF THE WINTER SEASON. (WIND SE.)

## THE DISTRIBUTION OF SALINITY IN MAY.

The course of the  $37^{\circ}/_{\infty}$  isohaline gives a clear indication of the wind-driven surface current to be expected in this season. It comes in from the surface water of the Gulf of Aden. Between the surface layers and the deeper water is a very sudden discontinuity showing relatively enormous stability (Text-fig. 10). It occurs between 40 and 50 metres at Station 203, 30–40 metres at Station 204, and 60–80 metres at Station 206. It seems



TEXT-FIG. 2.

probable that this discontinuity marks the limiting depth to which active wind transport occurs, *i. e.* the depth of the wind-driven surface current.

Beyond Station 206 towards the Red Sea the isohalines gradually turn up on coming into the more highly saline water of the Red Sea. At Station 206 there is an interesting bend in all the isohalines from  $37^{\circ}/_{\infty}$  to  $40^{\circ}/_{\infty}$ . The explanation of these bends may be found in two different factors. It may be the beginning of the reverse stream characteristic of the summer season which has just begun; but more probably it is the point of meeting of the highly saline upward-moving deep Red Sea water with the inflowing lower salinity Gulf of Aden surface water. The distribution of temperature and oxygen supports the latter view.

The course of the  $40.5^{\circ}/_{\infty}$  isohaline shows clearly the upward movement of highly saline deep Red Sea water on the north of the barrier, and its subsequent downpouring into the Gulf of Aden.

A very interesting feature is seen at the extreme right of the figure between 60 and 140 metres. Here the isohalines run almost vertically and are very close together, falling rapidly from 39 to 36. This aggregation is no doubt due to the highly saline deep Red Sea current coming into contact with a mass of low salinity Gulf of Aden water. Schott (1929) has assumed that this water of very low salinity is part of the surface current flowing from the Gulf of Aden into the Red Sea at this season. But the general course of the isohalines suggest that this is not so, and that the surface current with its higher salinity ( $>36$  as against  $<36$ ) is derived almost entirely from the surface water of the Gulf of Aden, and that during this season this deeper water mass is almost entirely blocked from entrance to the Red Sea by the outflowing Red Sea current. No doubt as this low salinity mass comes into contact with the deep Red Sea water, some of it will be projected upwards and will then mix, at least to a limited extent, with the upper wind-driven current. But it seems clear that the great mass of the surface current, with very different salinity, temperature and oxygen, is of quite different origin.

At Station 204 there is a very definite bend in the  $37^{\circ}/_{\infty}$  isohaline. Probably this has its explanation in the tide-induced oscillations which Vercelli (1927) has already described.

The existence of a mass of water of salinity  $>40.5^{\circ}/_{\infty}$  on the outside of the barrier, with a break at the shallowest level (Station 204), suggests that here we have an indication of the phenomenon described by Vercelli (1927). He pointed out that the isohalines rose while the tide was flowing into the Red Sea, and possibly the break in the  $40.5$  isohaline is due to the state of the tide; in this case the outflow of water of a salinity  $40.5^{\circ}/_{\infty}$  would be a transitory phase, occurring at the flood tide. Such an explanation appears to be probable in view of the fact that the observations at Station 204 were taken between 9.20 and 10.40 a.m. on May 16th, 1934, on which day high tides, height 5.9 ft., occurred at Perim at 11.12 a.m., so that the tide was flooding. An alternative explanation is that there may be a deeper channel between the Red Sea and the Gulf of Aden. But our fairly complete "echo" soundings, which would hardly miss such a channel, as well as those already charted, show no indication of it.

With reference to the question left over by Schott (1929) as to whether the outflow of water of a salinity of  $38^{\circ}/_{\infty}$  was a continuous or temporary phenomenon, these observations seem to indicate that the former is the case. Especially is this so in view of the fact that the  $38^{\circ}/_{\infty}$  isohaline runs almost level from Stations 206 to 203. These stations were worked at hours 0710, 1920, 1301, *i.e.* over a 6-hour period, and so it is impossible that they can all be at the same stage in the oscillations which Vercelli has shown to have a period of approximately 12 hours. Thus it would seem that the continuity of the  $38^{\circ}/_{\infty}$  isohaline is permanent *at this season* over all stages of the tide.

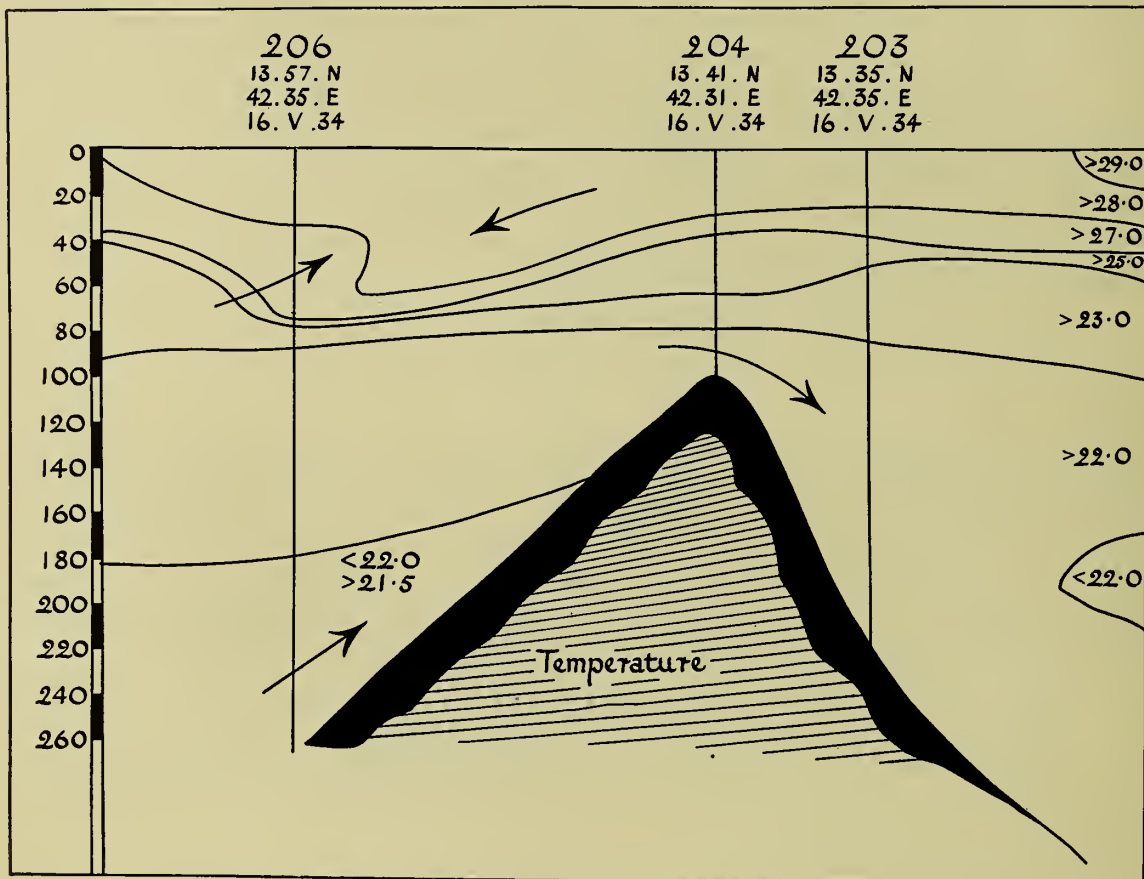
#### THE DISTRIBUTION OF TEMPERATURE IN MAY.

In Text-fig. 4 the course of the  $28^{\circ}$  isotherm marks off the wind-driven, warm current flowing from the Gulf of Aden into the Red Sea. Its very high temperature indicates that the water is almost entirely of surface origin. At Station 206 we have a sudden

bending of the  $28^{\circ}$ ,  $27^{\circ}$  and  $25^{\circ}$  C. isotherms, indicating that here the inflowing, warm surface current comes into contact with the "upwelling" deep Red Sea water. The nature of the change makes the other suggested explanation seem unlikely; but it is quite possible there is a large eddy here.

At Station 204 we see a bending of the  $25^{\circ}$  C. isotherm quite comparable with that seen at this point in the salinity figure, and with the same significance.

On the extreme right of the figure is a zone of low temperature at about 175 metres, indicating the presence of the low salinity water seen in the salinity figure. Its very low



TEXT-FIG. 3.

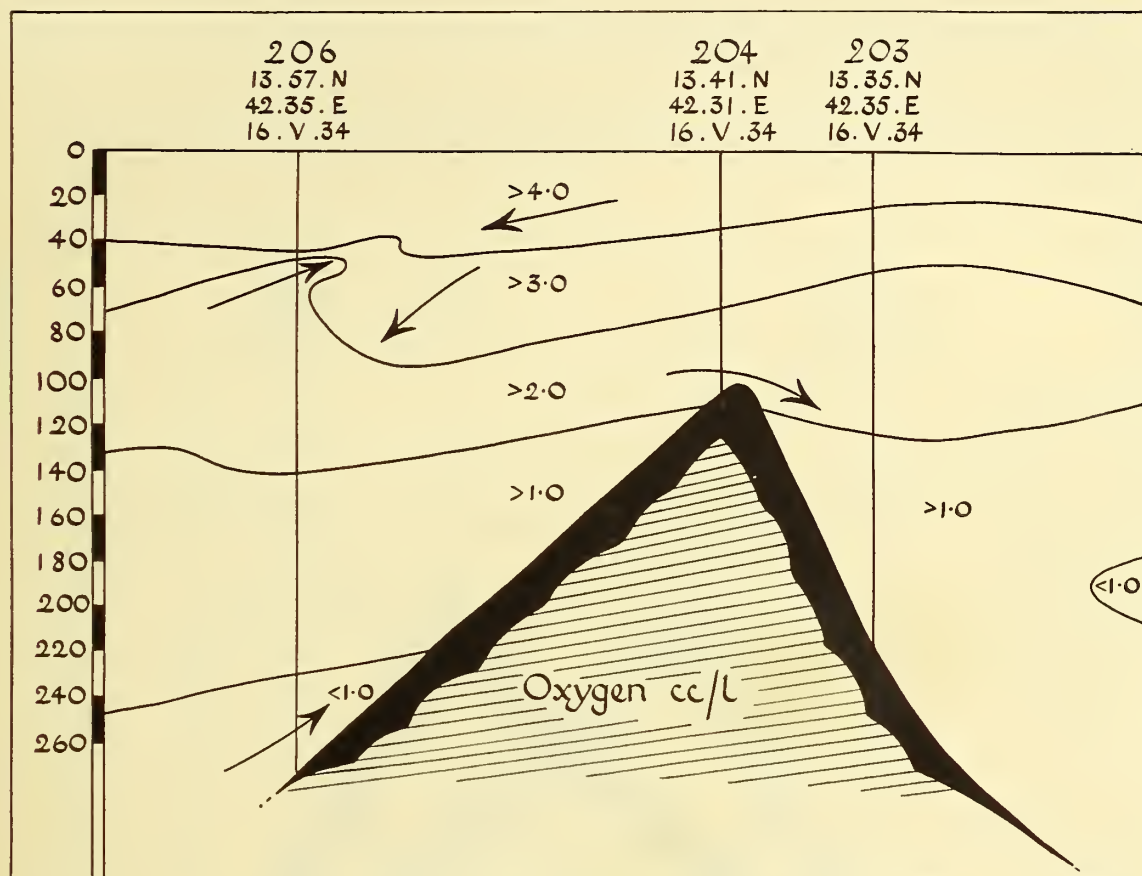
temperature makes it impossible that this mass of deep water can make any considerable contribution to the high temperature surface current, as suggested by Schott (1929).

#### THE DISTRIBUTION OF OXYGEN IN MAY.

In Text-fig. 4 the inflowing surface current is not very strongly indicated, but at Station 206 the bend in the 4 c.c./l and 3 c.c./l lines is further evidence that deep Red Sea water is here coming into contact with the inflowing surface stream. The course of the 1 c.c./l line within the Red Sea is a further indication of the deep upward movement in this region. On the extreme right of the figure a very low oxygen value is found at about 170 metres occupying the same position as the low salinity and low temperature water mass seen in the previous figures. The very low value of this oxygen is additional evidence



that there can be little mixing between this water and the highly oxygenated surface water flowing into the Red Sea.



TEXT-FIG. 4.

#### THE DISTRIBUTION OF DENSITY IN MAY.

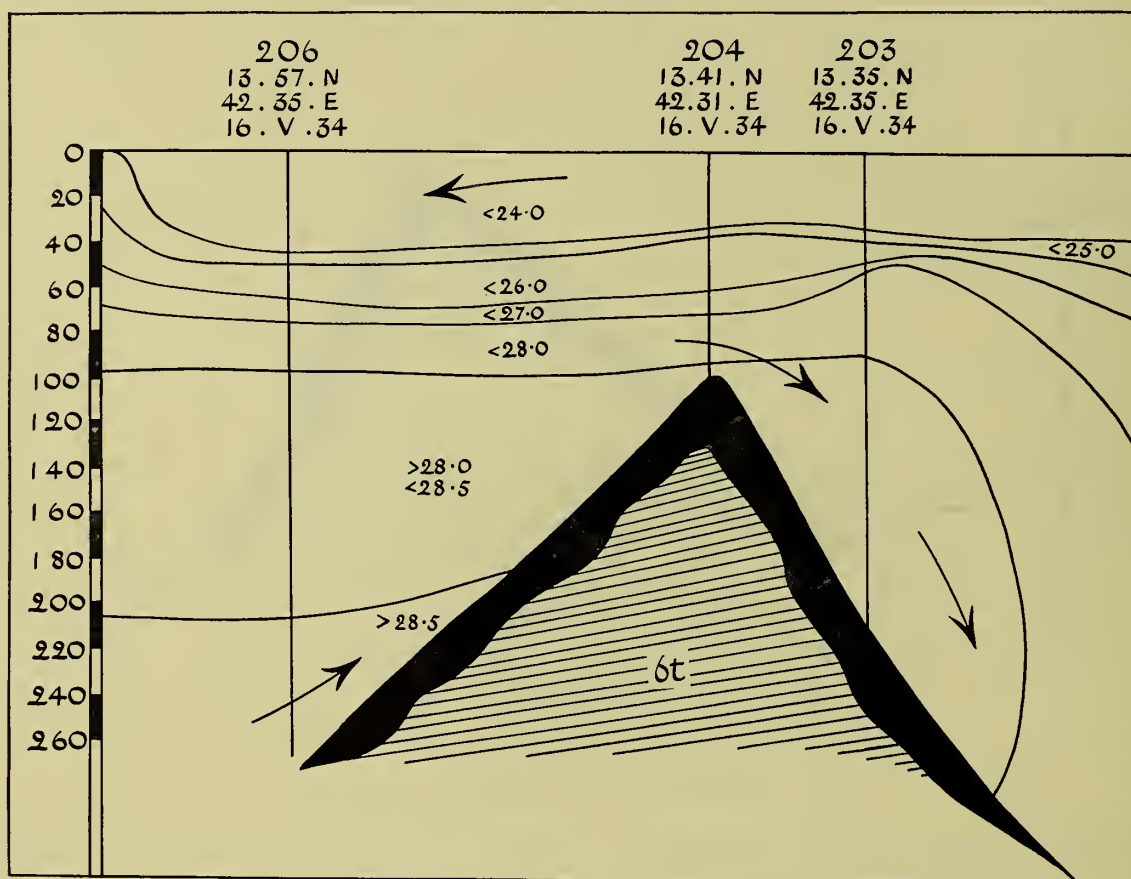
Here (Text-fig. 5) the indications of the inflowing surface stream are clearly marked by the 25.0 density line; and the outflowing deep Red Sea water is unmistakably seen in the down-curving of the 28.0 line beyond Station 203. The sudden change of density between the surface current and this deeper upward movement shows clearly the abrupt discontinuity between these two currents, which is so sharply defined that there can be little mixing between them. It is at this level that Vercelli (1927) found the maximum development of his tidal oscillations, and the great size of these is no doubt due to the great stability existing between these two water masses.

In these four figures the conditions prevailing at the end of the winter season are quite clearly shown. All the extensive investigations in this region have been carried out during this season; and this more detailed study enables us to amplify and correct the previous conclusions. The course of the inflowing surface current and the existence of an outward bottom movement, already recognized by previous workers, is unmistakable, but, whereas Schott (1929) derived this surface current largely from the water in the Gulf of Aden down to 200 metres, it is here shown that this deeper water can contribute but

slightly to the water in the surface current. The surface current is almost entirely derived from Gulf of Aden surface water; and the water below 100 metres is part of a totally different system, the origin of which will be considered in the next section.

No definite conclusion can be drawn from this work as to whether the  $38.0\text{‰}$  isohaline is always continuous over the "Sill"; but this is obviously so during the phase of the tide when Station 204 was carried out, and probably is so throughout *this season*.

Other conclusions which may be drawn from these figures will be discussed after the consideration of the summer season.



TEXT-FIG. 5.

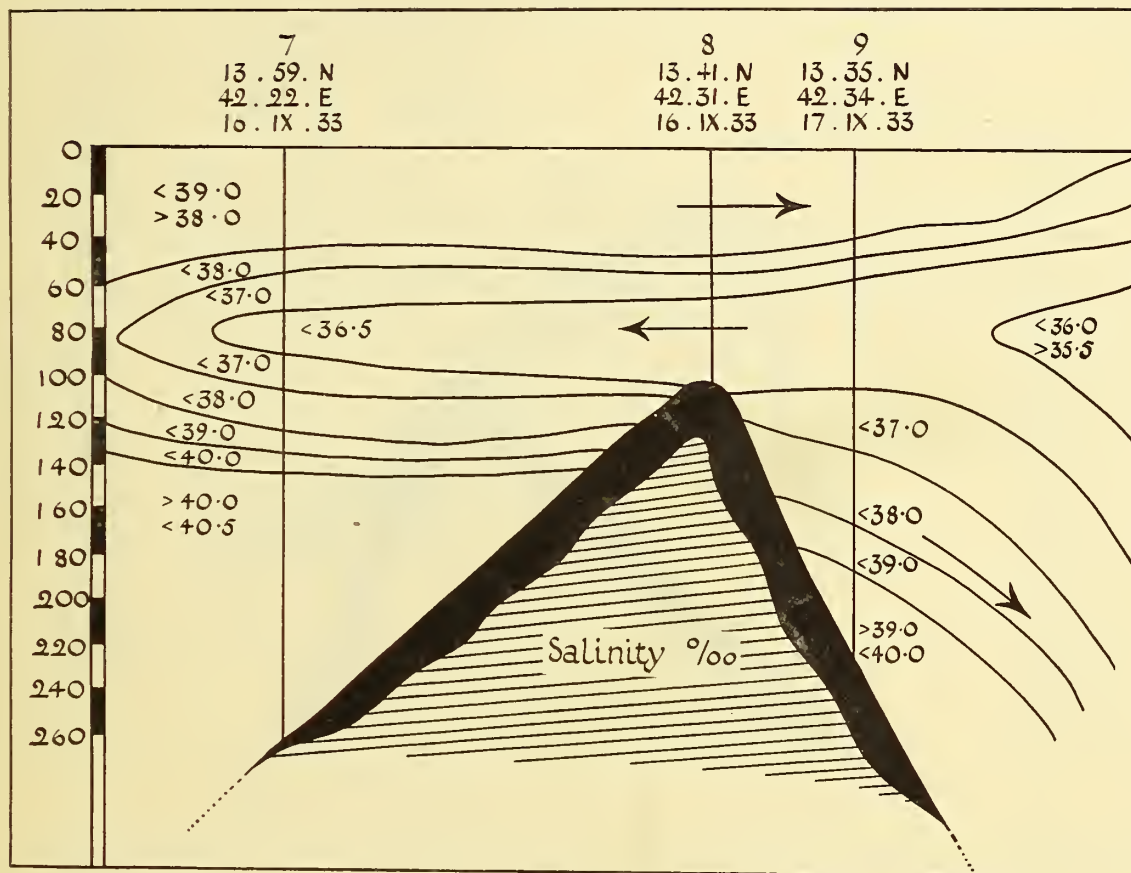
#### THE EXCHANGE AT THE END OF THE SUMMER SEASON. (WIND NNW.)

##### THE DISTRIBUTION OF SALINITY IN SEPTEMBER.

In Text-fig. 6 the course of the upper  $38.0\text{‰}$  isohaline clearly indicates the highly saline outflowing current from the Red Sea. This is to be expected in view of the NNW. wind blowing during this season. Below this line the salinity falls rapidly, reaching a minimum of less than  $36.5\text{‰}$  at about 80 metres. Below this point the salinity again rises rapidly. The course of the isohalines from the lower  $37.0$  line down to  $40.5$ , their upbending on the left of the figure and their down-curving from Station 9 out towards the Gulf of Aden indicates that here again we have an outflowing of Red Sea water from the deeper layers. At the "Sill" itself, however, these lines are interrupted, and it must

be assumed that they are continuous only during the flood tide and are at this season broken during the ebb. Such a conclusion would be in agreement with the vertical oscillations of the isohalines at the "neutral level" (Vercelli, 1927); in this connection it is significant that the size of the vertical oscillation necessary to make the  $39.5\text{‰}$  isohaline continuous at the sill is about 40 metres, the oscillation actually found here by Vercelli.

On the extreme right of the figure at about 80 metres we find the nucleus of the low salinity water found at 80 metres over the "Sill".



TEXT-FIG. 6.

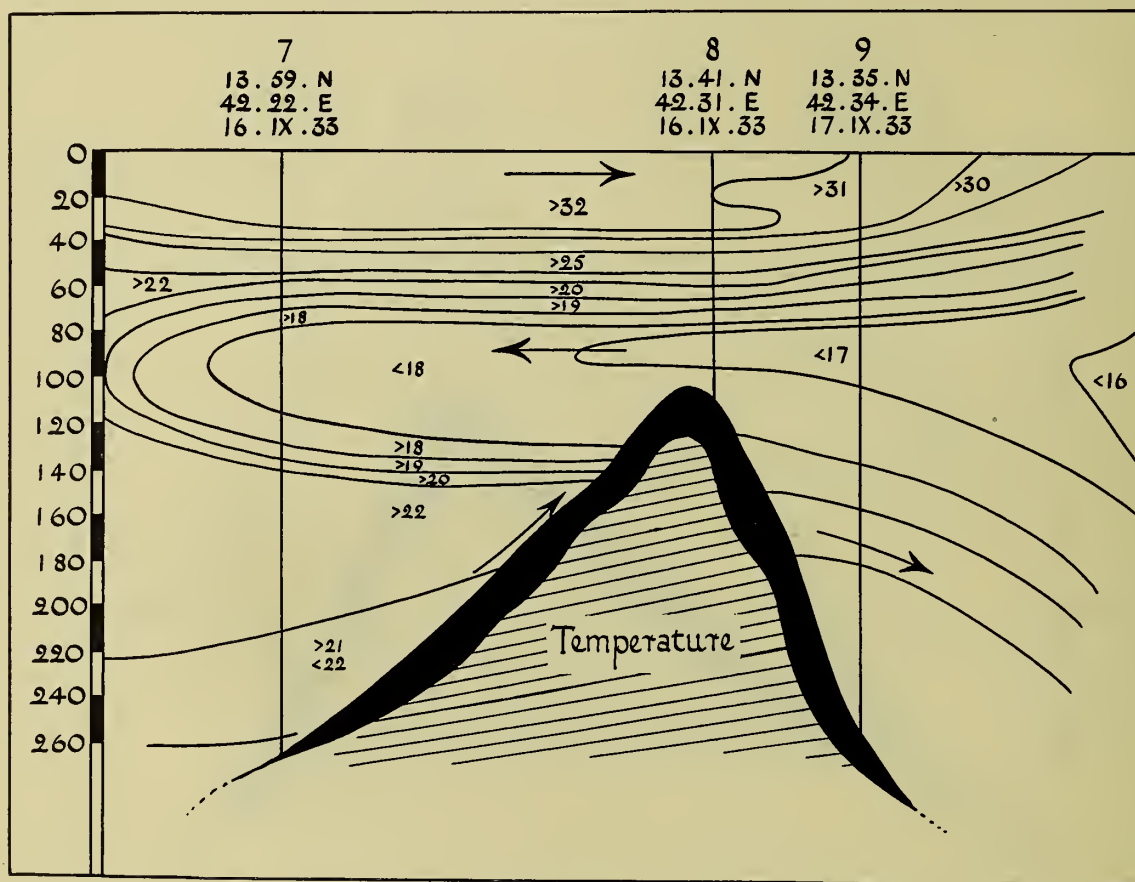
From this figure it can be seen that during this season there are three currents flowing over the "Sill", a surface wind-driven outflowing current of high salinity, a middle low salinity current with its nucleus at about 80 metres flowing into the Red Sea, and a deep highly saline body of water moving from the Red Sea to the Gulf of Aden presumably during the flood tide.

#### THE DISTRIBUTION OF TEMPERATURE IN SEPTEMBER.

As in the salinity section (Text-fig. 6), here (Text-fig. 7) we can recognize quite clearly the existence of three bodies of water. At the surface there is a very warm current flowing from the Red Sea to the Gulf of Aden, while below this there is a much colder stream in



the reverse direction, with its nucleus at about 80 metres. Below this point the temperature rises rapidly to about 22° C., and we here encounter the outpouring deep water from the Red Sea. At Stations 7, 8 and 9 the very rapid temperature discontinuity between these three bodies of water is clearly marked. The lower isotherms are interrupted at the "Sill", and the explanation of their reappearance on the Gulf of Aden side of the "Sill" is the same as that offered for the similar phenomenon seen in the isohalines, namely a tidal oscillation.

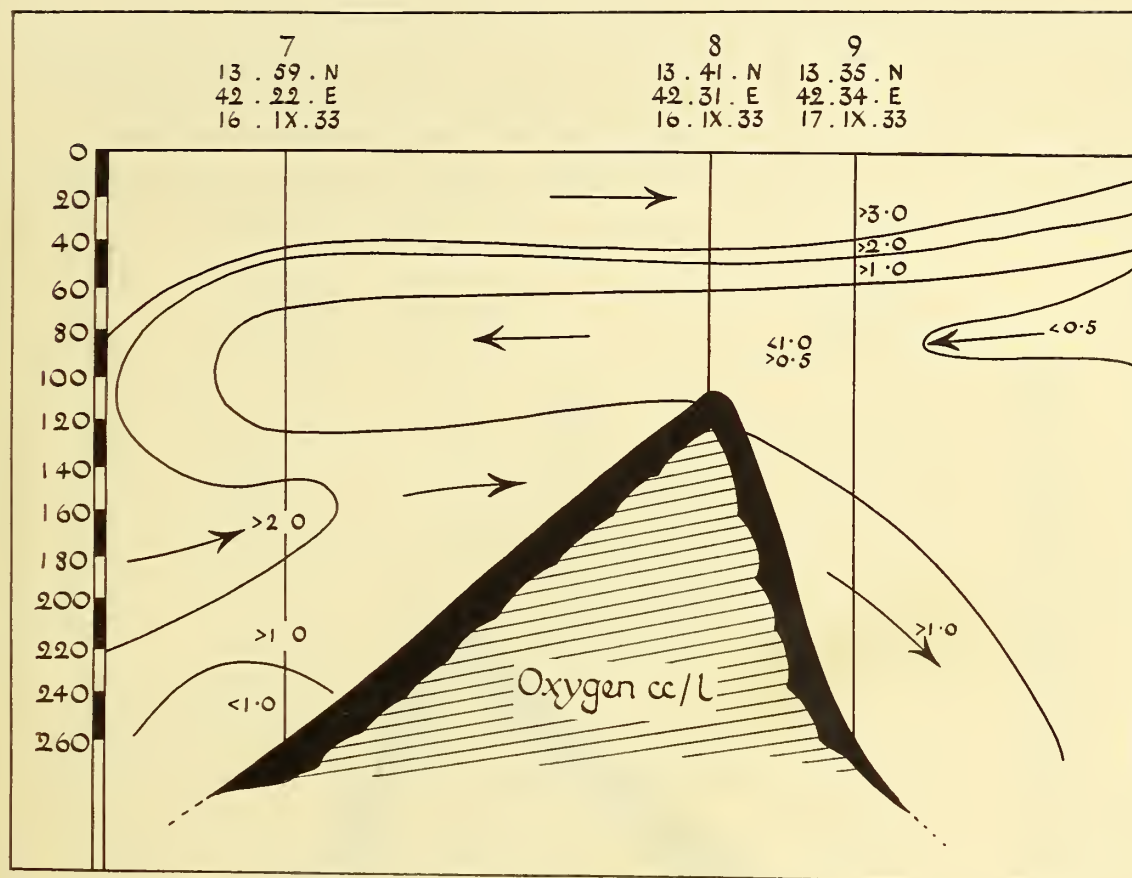


TEXT-FIG. 7.

#### THE DISTRIBUTION OF OXYGEN IN SEPTEMBER.

In Text-fig. 8 the three bodies of water already mentioned can again be seen. At the surface is the highly oxygenated outflowing Red Sea water, and below this is water with a very low oxygen concentration flowing from the Gulf of Aden to the Red Sea. Below 100 metres at Station 7 the rapid secondary rise of the oxygen shows that we have here entered the lowest body of water, the deep Red Sea stream. There is some overlap between the different currents, but the 1 c.c./l line approximately delimits the three bodies of water. The subsequent fall of oxygen at 240 metres at Station 7 might seem to suggest that here there is some admixture with the deoxygenated water from the Gulf of Aden, but as this is not indicated in the salinity or temperature figures, a more probable

explanation is that here we have a more or less stagnant portion of water caught between the seasonal oscillations of the Red Sea and the "Sill".



TEXT-FIG. 8.

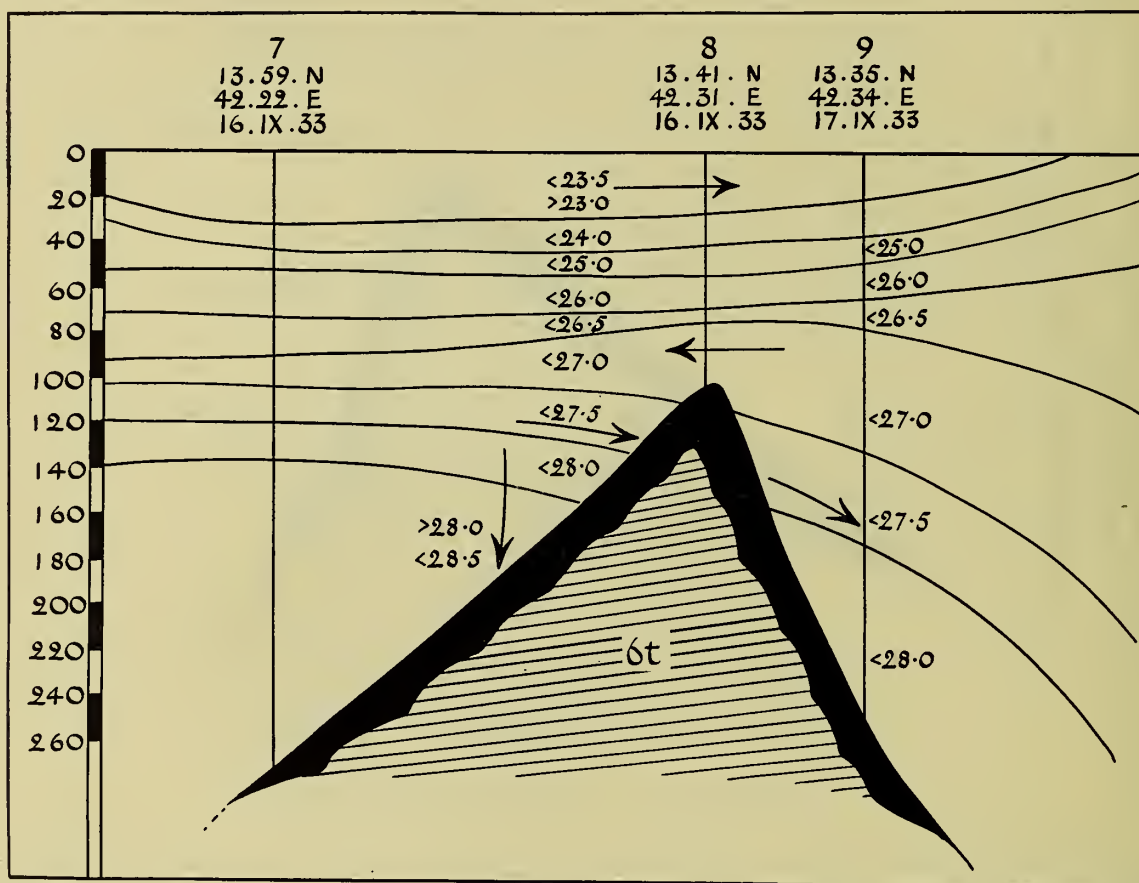
#### THE DISTRIBUTION OF DENSITY IN SEPTEMBER.

The phenomena already discussed in the previous three figures are not quite so clearly shown here; but the general trend of the three main bodies of water is quite definitely indicated. At the surface is a very light body of water due to the outflowing warm saline Red Sea stream roughly limited by the course of the 24.0 isostere; while at the bottom the course of the 27.0 and 27.5 density lines indicates the outpouring of deep Red Sea water. The inflowing subsurface Gulf of Aden stream is best indicated by the separation of the 26 and 26.5 density lines on the extreme right of the figure at a depth of about 80 metres and their subsequent convergence at Station 8. That these lines do not show the further passage of this current into the Red Sea is not due to great admixture of it with other bodies of water, but is due to the crowding together of the density lines over the "Sill". As with the salinity, temperature and oxygen figures, the lines showing the outflow of deep Red Sea water are not continuous over the "Sill". The probable explanation of this phenomenon has already been given.

From these four figures (6, 7, 8 and 9) it can be clearly seen that there are three bodies of water, distinct in both properties and origin, flowing over the "Sill". At the surface

there is the light, high temperature, high oxygen, and high salinity water flowing from the Red Sea to the Gulf of Aden under the influence of the prevailing NNW. winds of this season. This flow extends to various depths, but shows an average depth of about 40–50 metres. Below this is a low salinity, low temperature and low oxygen body of water, of moderate density flowing from the Gulf of Aden to the Red Sea to compensate for the water lost from here by evaporation and in the wind- and bottom-currents.

At the bottom there is every indication that there is a temporary outflow of deep Red Sea water of very high salinity, high density, comparatively high oxygen concentration



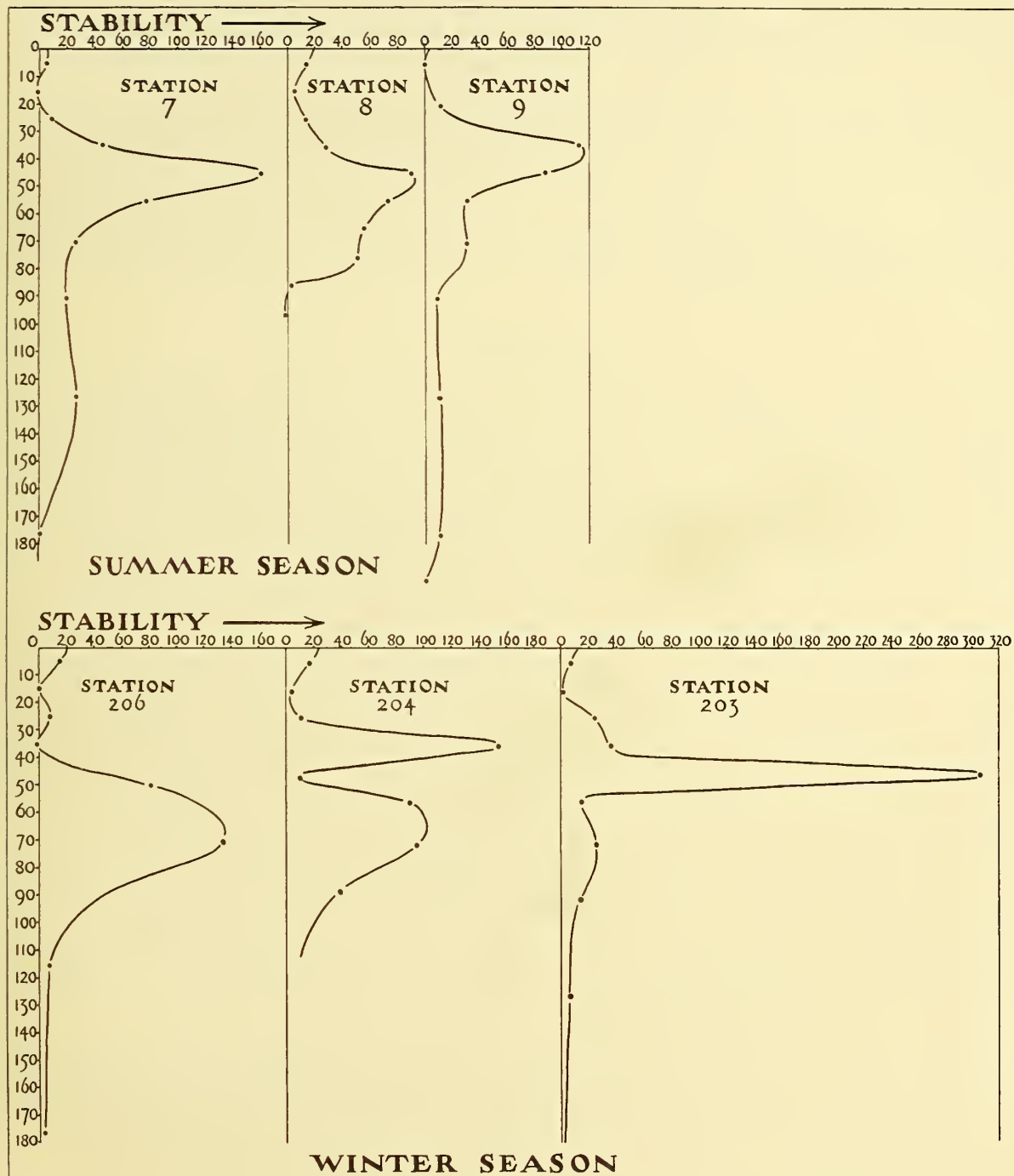
TEXT-FIG. 9.

and moderate temperature. This flow, however, is almost certainly transitory, occurring only during the flood tide in accordance with the observations of Vercelli (1927).

A comparison of the winter and summer seasons elucidates many of the points which previous workers have been forced to neglect through lack of knowledge of the summer conditions and of the circulation of the Red Sea, which I have discussed in a previous paper (Thompson, 1939). In the first place it has been shown that the type of circulation in the two seasons is essentially different. While in the summer there are three distinct water masses moving over the "Sill", in the winter months we have but two, the middle one having now disappeared and the surface one now moving in the opposite direction, and having a different source. The conclusions of Schott (1929), in which he considered that the inflowing winter current was continuous with the Gulf of Aden water below



100 metres, has been shown to be entirely erroneous. The lower part of the current is really part of the middle summer current shown in the figures for this season, and which is completely blocked in the winter by the increased outflow of deep Red Sea water.



TEXT-FIG. 10.

The outflow of deep Red Sea water is shown to be very much greater in the winter than in the summer months, and while this may be due in part to the state of the tide during these observations, the explanation is probably to be found in the nature of the

Red Sea circulation previously described (Thompson, 1939). It was there shown that during the winter months there would tend to be an upward movement of the deep Red Sea water against the "Sill", while during the summer the movement would be in the opposite direction. Such a movement would tend to push this water over the "Sill" in the winter months, and hinder its passage in this direction during the other season. In addition the production of this deep highly saline water is confined to the mid-winter months. This also would tend to increase its outflow in the winter season.

Schott, in his conclusions on this area, points out that the winds during the summer season would be such as to retard the inflow of water into the Red Sea just at that period when, evaporation being at a maximum, a compensating inflowing current would be most needed. The solution to this problem is found in the nature of the summer circulation as here described, the necessary compensation for evaporation being provided by the cold inflowing intermediate stream.

### SUMMARY.

1. It is shown that the exchange over the "Sill" between the Red Sea and the Gulf of Aden is fundamentally different in the winter and summer seasons. In the winter there are but two masses of water moving over the "Sill," a surface very warm layer entering the Red Sea from the Gulf of Aden, and a deep outflow of very saline water from the Red Sea. In the summer there are three bodies of water moving over the "Sill"; a wind-driven surface mass of high temperature water flowing out of the Red Sea into the Gulf of Aden; a bottom very saline outflow from the Red Sea; and an intermediate low salinity low temperature inflow from the Gulf of Aden into the Red Sea.

2. Schott has confused the *Winter Surface* inflow with the Summer *intermediate* inflow. It is shown here that these two bodies of water are of entirely different characteristics, contribute but little to each other, and are confined in this region to opposite seasons. Schott's confusion of these two bodies of water prevented him from explaining the compensation for evaporation and other losses in the Red Sea during the summer season. It seems clear from the previous discussions that this compensation is effected by the cold, low salinity intermediate stream which is confined to the summer season.

3. It is shown that the outflow of highly saline deep Red Sea water is much greater during the winter than the summer months. This is due to: (a) This water is being produced at this season in the northern Red Sea; (b) the rotational effect due to the inflowing surface water which piles up in the region of latitude 20° N., and projects the deep Red Sea water up over the "Sill".

4. It is suggested that the outflow of this deep Red Sea water is effected by tidal oscillations in such a way that the flow is at a maximum over the flood, and at a minimum over the ebb tide. While the interruption of the deep outflow at the ebb tide seems to be complete during the summer, it appears that this is never so in the winter months.

### ACKNOWLEDGMENT.

I am indebted to Mr. C. O'D. Iselin and Dr. J. F. G. Wheeler for numerous corrections to the manuscript of this paper; and to the Woods Hole Oceanographic Institution for facilities during its compilation.

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INVESTIGATIONS

THE DISTRIBUTION OF HYDROGEN-ION CONCENTRATION  
IN THE NORTH-WESTERN INDIAN  
OCEAN AND ADJACENT WATERS

BY

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WITH THIRTY FOUR TEXT FIGURES



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# CHEMICAL AND PHYSICAL INVESTIGATIONS

## THE DISTRIBUTION OF HYDROGEN-ION CONCENTRATION IN THE NORTH-WESTERN INDIAN OCEAN AND ADJACENT WATERS

WITH AN APPENDIX ON THE DETERMINATION OF HYDROGEN SULPHIDE IN SEA-WATER WITHDRAWN FROM CERTAIN SAMPLES OF MUD COLLECTED FROM THE NORTH-WESTERN INDIAN OCEAN\*

BY

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(Faculty of Science, the University, Cairo)

WITH THIRTY-FOUR TEXT-FIGURES.

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\* It is not possible, in present circumstances, to publish the Tables of Data referred to in this Report; the Tables are preserved in the library of the British Museum (Nat. Hist.), where they are available for reference.



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## INTRODUCTION.

A KNOWLEDGE of hydrogen-ion concentration in sea-water is of prime importance in the study of the ocean. This quantity plays a governing rôle in the vital processes, conditions of existence and distribution of marine plants and animals. It provides the geochemist with valuable information in connection with the formation and re-solution of marine calcareous sediments. It may also prove, if accurately measured and properly corrected, of great aid to the oceanographer, at least from a qualitative point of view, in tracing the origin, history and movement of water masses.

The determination of hydrogen-ion concentration has been, in fact, one of the most attractive lines of the physical chemistry of the sea. In recent years attention has been turned to the study of the complex of physical and chemical factors—the so-called buffer mechanism—that determine and control the variation of hydrogen-ion concentration in sea-water (Henderson and Cohn, 1916; Buch, 1917; McClendon, 1917*a*; Schulz, 1921; Irving, 1925; Kreps, 1926; Saunders, 1926; Buch, 1930; Kändler, 1930; Thompson and Bonnar, 1931; Buch, Harvey, Wattenberg and Gripenberg, 1932; Gee, Moberg, Greenberg and Revelle, 1932; Buch, 1933; Wattenberg, 1933; Moberg, Greenberg, Revelle and Allen, 1934).

No attempt, however, is made in the present report to deal with this mechanism, since unfortunately not all the factors which are essential to its full discussion were experimentally determined. The experimental material on which this report has been based is limited to serial measurements of hydrogen-ion concentration.

The earliest quantitative contribution to our knowledge of hydrogen-ion concentration in sea-water was made by Ringer in 1908, whereas the first measurements over extended areas were made by Palitzsch in 1910 on the "Thor" (Palitzsch, 1912). Since then extensive observations have been made on the waters of several seas and oceans. These observations can be classified, for the purpose of surveying them, into three categories: (1) Observations made by expeditions, (2) observations made during more or less regular

cruises of vessels belonging to various countries—mainly to those who are members of the International Council for the Exploration of the Sea—and institutions, and (3) scattered observations by many investigators.

To the first category belong the observations made by the Danish Oceanographical Expedition on the “Thor” to the Mediterranean and adjoining seas in 1910 (Palitzsch, 1912); by the German Antarctic Expedition in the “Deutschland” in 1911–1912 (Brennecke, 1921); during the cruises of the “Armauer-Hansen” in the North-Eastern Atlantic in 1913 and 1914 (Helland-Hansen, 1914; Gaarder, 1927); by the Norwegian North Polar Expedition in the “Maud” in 1922–1924 (Sverdrup, 1929); by the German Atlantic Expedition in the “Meteor” in 1925–1927 (Wattenberg, 1933); by the “Discovery” in the South Atlantic in 1925–1927 (“Discovery” Reports, Vol. I, 1929); by the Great Barrier Reef Expedition in 1928–1929 (Orr, 1933); by the “Discovery II” in the South Atlantic and in the South-Western Indian Ocean (“Discovery” Reports, Vol. IV, 1932); by the “Nautilus” Expedition in the high latitudes of the North Atlantic in 1931 (Sverdrup, 1933).

The observations belonging to the second category are mainly published in the ‘Bulletin Hydrographique’, 1921–1934. To this category belong the observations made by Finland in the Gulf of Finland and the Baltic in 1926–1934; by Norway in the Atlantic, Davis Strait, etc., 1924, in several fjords in 1928 (M.S. “Johan Hjort”) and in the North Sea and the Atlantic in 1929–1933 (M.S. “Johan Hjort”), and 1934 (M.S. “Armauer-Hansen”); by Denmark in the Cattegat, Belts, Baltic and Sound, in 1923 in the North Sea, Cattegat, etc., and the Atlantic in 1925–1926, and in the Atlantic in 1928 (“Godthaab”), and 1931 (“Dana”); by Germany in the Baltic in 1926, 1929, 1931 and 1933 (“Poseidon”); by England in the North Sea in 1921; by Scotland in the North Sea in 1932 (H.M.S. “Challenger” and “Explorer”); by Lithuania in the Baltic in 1934 (S.S. “Hidrografs”); by Portugal off the Portugal coast in 1934 (S.S. “Albacora”), by Japan in the Japanese waters in the Pacific in 1930–1935 (R.M.S. “Syunpu Maru” and the Training-ship “Skintoku Maru”); by Woods Hole Station of U.S.A. in the Atlantic in 1932–1934 (M.Y. “Atlantis”); by the State Oceanographical Institute of U.S.S.R. in the Barents Sea in 1927–1930 (Brujewicz, 1931).

To the third category of observations belong those made by Ringer (1908) on the waters of the Zuider Zee, North Sea and Bømmel Fjord; by Buch (1914) on the waters of Pojowiek; by Moore, Prideaux and Herdman (1915) on the Irish Sea waters; by Nansen (1915) on the Spitzbergen waters; by McClendon (1917*b*) on Tortugas waters; by Gaarder (1917) on the waters off the Norwegian coast and fjords; by Buch (1917) on the waters of the Gulf of Finland and the Baltic; by McClendon (1917) on waters from San Diego and waters from the Gulf Stream off Miami and Florida; by Mayer (1917) on the surface waters of the tropical Pacific; by Gail (1919) on the waters in the region of the Puget Sound; by Mayer (1919) on the waters of the Pacific from Fiji to Honolulu, Samoa, and San Francisco; by Crozier (1920) on the water in the lagoons at Bermuda; by Powers (1920) on the Pacific waters; by Michael (1921) on the waters off the coast of southern California; by Atkins (1922) on the sea-water off Plymouth Sound and the adjacent parts of the English Channel; by Cameron and Mounce (1922) on the waters in the Strait of Georgia and adjacent waters; by Labbé (1922) on the waters at Croisic and Batz; by Legendre (1922) on the water at Concarneau; by Mayer (1922) on the tropical waters of the Atlantic and Pacific; by Schulz (1922) on the North Sea and the Baltic Sea



waters ; by Atkins (1923) on the English Channel waters ; by Legendre (1923) on the Concarneau waters ; by Schultz (1923) on the Baltic waters ; by Allee (1923) on the waters in the vicinity of Woods Hole ; by Legendre (1924) on the waters in the Bay of Concarneau ; by Bruce (1925) on the waters of Port Erin Bay ; by Atkins (1926) on the English Channel waters ; by Kreps (1926) on the waters from Kola Fjord in the Arctic ; by Moberg (1926) on the waters off the coast of the southern California ; by Marshall and Orr (1927) on the waters in the Clyde Sea area ; by Ito (1928) on the water in the south-western portion of the north Pacific ; by Moberg (1928) on the sea-water off the coast of southern California by Seiwel (1928) on the surface waters of the English Channel and the southern North Sea ; by Bini on the waters of the southern Red Sea (1929) ; by Johnson and Thompson (1929) on the sea-water at the Puget Sound Biological Station ; by Thompson, Miller, Hitching and Todd (1929) on the Puget Sound waters ; by Reiss and Vellinger (1929) on the sea-water in the vicinity of Tunis ; by Wimpenny (1930) on the Suez Canal water ; by Schulz (1931) on the surface waters between Iceland and Greenland ; by Seiwel (1931) on the waters of the North Sea, the southern entrance to the Norwegian Sea and the water south of Iceland ; by Zanco (1931) on the Calgiari waters ; by Kreps and Verjbinskaya (1932) on the waters of the Barents Sea ; by Marchand (1932) on the waters in the vicinity of the Cape Point ; by Zanco (1932) on the waters at Calgiari ; by Cooper (1933*a, b*) on the waters of the English Channel ; by Miller (1934) on the surface waters between Hong-Kong and England by way of the Cape of Good Hope, including observations in the Indian Ocean between Colombo and Mombasa.\*

From the foregoing survey it will be seen that, with the exception of the few surface observations made by Miller on the surface waters between Colombo and Mombasa, no systematic measurements of hydrogen-ion concentration have been made on the waters of the north-western Indian Ocean prior to the John Murray Expedition in 1933-1934.

In the present report it is therefore intended to record, describe and discuss the distribution of hydrogen-ion concentration values observed by the John Murray Expedition in H.E.M.S. "Mabahiss" in the Indian Ocean.

To express the magnitude of hydrogen-ion concentration more simply, Sørensen (1909) proposed that instead of the numerical value itself, its common logarithm with the negative sign omitted should be employed, and he called this figure the hydrogen-ion exponent, pH. Throughout this report this mode of expressing the hydrogen-ion concentration will be followed.

#### AREA OF INVESTIGATION.

The observations recorded in this report were made during the following cruises of H.E.M.S. "Mabahiss" into the Indian Ocean in 1933-1934 :

Cruise.	Stations.	Dates.
1. Red Sea to Aden . .	7-9, 12-14, 17 .	September 9th to 22nd, 1933.
2. Aden to Aden . .	19-23, 25, 32 .	September 28th to October 17th, 1933.
3. Aden to Karachi . .	38-41, 43, 46, 47, . 49-52, 60 .	October 21st to November 10th, 1933.

\* This survey, which covers observations published until 1934, is by no means complete and merely serves as a guide to more detailed information as well as to geographical distribution of observations.



Cruise.	Stations.	Dates.
4. Karachi to Bombay.	76, 81-83	November 17th to December 8th, 1933.
5. Bombay to Mombasa	91-93, 95, 97, 101, 102	December 13th to 31st, 1933.
6. Mombasa to Zanzibar	116-118	January 9th to 24th, 1934.
7. Zanzibar to Colombo	127-134	January 30th to February 22nd, 1934.
8. Colombo to Colombo	136, 145	March 17th to April 13th, 1934.
9. Colombo to Aden	166, 167, 169-171, 173-175, 181, 183, 187, 195	April 19th to May 8th, 1934.
10. Aden to Red Sea	197-204, 206, 208	May 14th to 21st, 1934.

Text-fig. 1 shows the positions of the various sections and the locations of the stations at which pH observations were made. The sections are denoted by letters and the stations by numbers, which are to be found in the List of Stations (Sewell, 1935), where information regarding position, date, time, depth, meteorological conditions, etc. can be found.

### METHOD.

For the measurement of pH of sea-water on board the "Mabahiss" the colorimetric method was used. Accurate measurements of pH by this method dates from the pioneer work of Sørensen (1909). The method was developed for hydrographic investigations by Sørensen and Palitzsch (1910).

The principle of the method consists in adding to a measured sample of sea-water, whose pH is to be determined, a measured volume of a suitable indicator and comparing the colour so produced with that of the same indicator in standard solutions of known pH. These pH-known solutions, or "standard reference solutions" as they are called, are buffer mixtures prepared by mixing two buffer solutions in certain proportions and determining their pH electrometrically. The colorimetric method is therefore a comparative one, and its accuracy depends primarily on the accuracy of the electrometric method, which is assumed to give correct and absolute results.\*

Under the various sub-headings in this section the technique employed in preparing the buffer solutions, indicators and standard reference solutions and in measuring the pH of sea-water samples will be described; the effects of salts, temperature and pressure on the colorimetric determination of pH will also be discussed.

### BUFFER SOLUTIONS.

McClendon borax-boric acid buffer mixtures (McClendon, 1917*a*) were employed. Two stock buffer solutions of borax (28.67 gm. of borax + 22.50 gm. of sodium chloride per litre) and boric acid (18.60 gm. of boric acid + 22.50 gm. of sodium chloride per litre) were prepared from Analar chemicals which received no further purification. The

\* Brønsted and Grove (1930) stated, however, that the electrometric method cannot be considered as the most reliable method for accurate determinations of hydrogen-ion concentration since measurements by this method are considerably affected by salts.

water used in preparing these solutions was twice re-distilled, boiled to remove dissolved carbon dioxide and finally cooled in a tightly-stoppered flask. As soon as each solution was prepared it was introduced into a waxed bottle which had been fitted with a soda-lime tube and filled with  $\text{CO}_2$ -free air. Each bottle was connected with a 10 c.c. burette reading to 0.05 c.c. Both burettes were also fitted with soda-lime tubes.

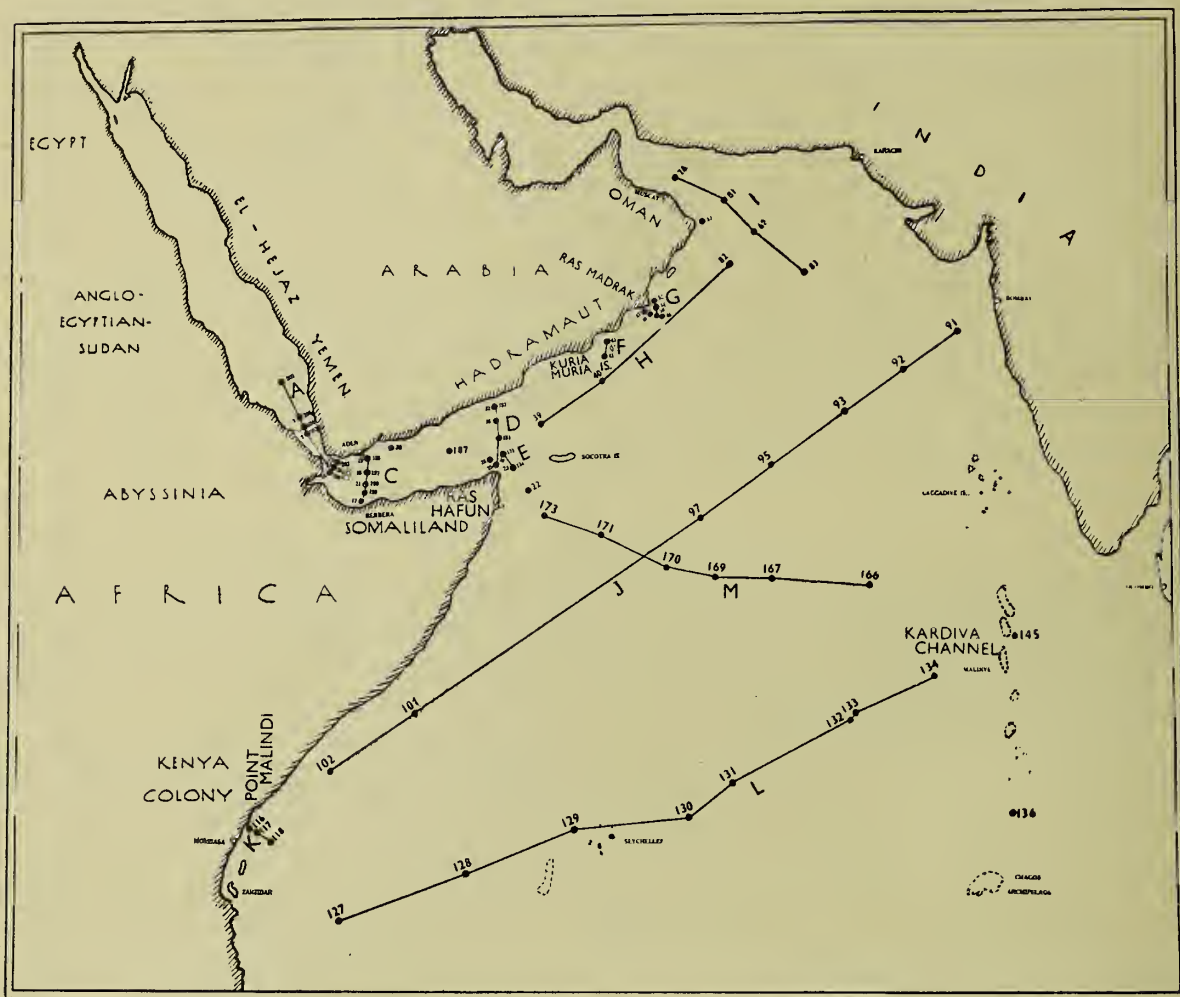


FIG. 1.—SHOWING THE POSITIONS OF STATIONS AT WHICH pH OBSERVATIONS WERE MADE

#### INDICATORS.

Three indicators were used, namely, cresol red, thymol blue, and phenol red. For preparing indicator solutions Clark's method (Clark, 1928) was employed. This consists in dissolving the indicator in the theoretical amount of base necessary to form the salt, and then diluting with water to the required concentration. This method of preparing aqueous solutions of indicators was used in preference to other methods in which alcohol is used as a solvent, since it was anticipated that in the tropical regions it would be very difficult to prevent completely the alcoholic solution becoming concentrated by evaporation while in actual use.

The following stock solutions of indicators were prepared: 0.2% cresol red, 0.2% phenol red, and 0.4% thymol blue. These stock solutions were stored in well-stoppered

waxed bottles. From these solutions the more dilute concentrations, 0.02%, 0.02%, and 0.04% respectively, used in the actual pH measurements were prepared as needed.

#### STANDARD REFERENCE SOLUTIONS.

Thin monax test-tubes were chosen to contain the standard reference solutions. The tubes were cleaned with chromic acid mixture, distilled water and then steamed for a considerable time. They were left to drain and were finally dried in an air oven at 110° C. The tubes were carefully graded, and only those having the same bore were used. Each tube was then constricted near the top to a narrow neck, filled with buffer solutions in correct proportions as given by McClendon (1917*a*) and quickly sealed so as to avoid CO<sub>2</sub> getting in. The total volume of buffer mixture in each standard tube was 10 c.c. against 30 c.c. used by McClendon. The procedure followed in filling each tube was first to place in it one drop of purified toluene, the indicator solution (0.5 c.c.), the borax solution, and finally the boric acid solution. Toluene was added to obviate the action of glass and to prevent the growth of moulds, so that the pH would not alter on keeping (Atkins, 1922). The tubes were labelled so as to give valid readings when used for measuring the pH of sea-water with a salinity of *ca.* 33‰.\* The pH interval between the consecutive tubes of the scale was 0.02 unit.

Three sets of buffer standards were prepared; each set was contained in a specially-made wooden box. The range covered by each set was from pH = 7.00 to pH = 8.80; and the range of use of each indicator was as follows: Phenol red, 7.00–8.10; cresol red, 7.50–8.40; thymol blue, 8.20–8.80. The tubes were kept in the dark when not in use, in order to avoid the bleaching action of light. Only one set of buffer standards was used on the present Expedition, and it was checked now and again against one or the other of the two additional sets, which were kept all the time unexposed to light. No fading was detected during the period of nine months.

#### SAMPLES OF SEA-WATER FOR pH DETERMINATION.

When taking the sea-water samples for pH determination the sample bottle was almost completely filled, a small or no air space being left over the water. As a rule the pH was determined on the day of collection or occasionally on the following morning, in which case the samples were preserved on collection with one drop of a saturated solution of mercuric chloride to stop the activity of micro-organisms. It was shown by Ibanez (1931) that under these conditions there was little or no change in the CO<sub>2</sub> content of the sample.

#### MEASURING THE pH OF THE SEA-WATER SAMPLE.

Ten c.c. of the sea-water sample were added to 0.5 c.c. of the indicator solution which had been measured into a test-tube of equal bore to the tubes of the standard set. The colour comparison with the standard tubes was then made by the eye, usually under diffused daylight against a white background, but occasionally under artificial light. When the matching of the sample and the standard was completed, the pH value marked

\* This validity was assumed in the belief that the salt-error corrections found by McClendon were accurate. Czyhirin (1931) has, however, shown, as will be described later, that these corrections were misleading. These readings became therefore subject to further corrections.



on the latter, as well as the temperature of measurement, was recorded. With practice it was possible to make the colorimetric determination in a few seconds.

Cresol red was found to be the most useful indicator which satisfactorily covers the whole range of pH met with in the north-western Indian Ocean. Thymol blue was used for confirmatory determination over the more alkaline range, and phenol red over the less alkaline range.

#### THE EFFECT OF SEA-SALT ON THE COLORIMETRIC MEASUREMENT OF pH.

It is well known that the colorimetric method of measuring hydrogen-ion concentration is subject to certain errors, which should be corrected if results identical with those of the electrometric method are to be obtained. In his fundamental work Sørensen was aware of the effect of salts on the colours of indicators, and Sørensen and Palitzsch (1913) determined the salt-error corrections for several indicators. Their method of determining the salt-error of an indicator in sea-water consisted in acidifying the sea-water and passing hydrogen through to displace carbon dioxide, then neutralizing the sea-water to the range of the indicator under examination with buffer mixture, and finally comparing the colorimetric with the electrometric measurements. Commenting on this method of determining the salt-error, Clark (1928, p. 182) states that "such calibration is one of the very best ways to deal with the salt-error, since it tends to bring measurements to a common experimental system of reference". Sørensen and Palitzsch's work was followed by that of several investigators, who made more or less detailed experimental study of the salt-errors of indicators (Wells, 1920; Kolthoff, 1922; Ramage and Miller, 1925; Czyhirin, 1931; Brujewicz and Skopintzew, 1933; Buch and Gustafsson, 1934; Mitchell and Taylor, 1935; Mitchell, Buch and Rakestraw, 1936). Because of the lack of uniformity in the methods used in the determination of the salt-error of the same indicator in sea-water, however, different salt-error corrections were applied to measurements of pH in sea-water.

This, added to the fact that various methods and buffer standards have been used in measurement of the pH of sea-water, makes the existing data tedious and difficult to compare. For instance, the discordance between pH values obtained by using Palitzsch buffer standards (Palitzsch, 1915) and those obtained by using McClendon buffer standards (McClendon, 1917*a*) after applying the salt-error correction conformable to each set of standards, was found to be striking (Czyhirin, 1931; Brujewicz and Skopintzew, 1933). Palitzsch's buffer standards have been in common use in marine investigations of pH. The fact that we have used McClendon's buffer standards on the "Mabahiss" makes this disagreement of a special interest to us and worthy of our consideration.

According to McClendon, his borax-boric acid buffer standards give correct readings (*i. e.* identical with electrometric measurements) when used for measuring the pH of sea-water which has a salinity of *ca.* 33‰, and a slight salt-error correction has to be applied for other salinities. McClendon determined the salt-error of cresol red and thymol blue. His method differed, however, from Sørensen and Palitzsch's, which has been in general use, in that he used for his determinations samples of natural sea-water which had not been neutralized.

Recently Czyhirin (1931) made new determinations of the salt-error of cresol red in sea-water when McClendon buffer standards are used as a comparison scale. He employed the usual method of salt-error determination (Sørensen and Palitzsch, 1913). The

electrometric determination was carried out in a hydrogen electrode and the accuracy of both the electrometric and colorimetric determinations is claimed to be  $\pm 0.01$  pH.

From his determinations Czyhirin found a considerable divergence in the magnitude of the salt-error correction as determined by his own measurements and as given by McClendon. Czyhirin attributed this divergence to the fact that he used sea-water in which the carbonate buffer system was replaced by the borate system, as has been the case in the determination of nearly all known salt-errors, while McClendon used natural sea-water with a carbonate buffer system. Applying his salt-error corrections, determined for cresol red and McClendon buffer scale, Czyhirin obtained pH values identical with those obtained by the same indicator and Palitzsch buffer scale. The work of Czyhirin was later confirmed by Brujewicz and Skopintzew (1933).\*

All our pH observations were corrected for the salt-effect by applying the corrections of Czyhirin (1931).

#### THE TEMPERATURE EFFECT ON THE COLORIMETRIC MEASUREMENT OF pH.

The influence of temperature on the colorimetric determination of pH had been studied by only a few investigators (Walbaum, 1920; McClendon, 1917*a*; Kolthoff and Bosch, 1927) before Buch published the results of his studies (Buch, 1929). From a systematic investigation of the influence of temperature on the dissociation constants of various indicators, when admixed with buffer mixtures and with sea-water, on the pH of buffer mixtures and on the pH of sea-water, Buch showed that the temperature plays a complex part in the colorimetric measurement of pH of sea-water, and that, in order to get accurate results, observations should be corrected for the temperature effect.

As a result of spectrophotometric measurements of the absorption of light by various indicators when admixed with buffer mixtures and with sea-water at varying temperatures, Buch proposed the following equation for the reduction of the observed pH values to the temperature of the water *in situ*:

$$\text{pH}_w = \text{pH}_b + a(t_b - t_w) + \beta(t'_w - t_w)$$

where  $\text{pH}_w$  = the pH of sea-water at its temperature *in situ*,

$\text{pH}_b$  = the pH of the matching standard buffer tube reduced to the temperature of measurement,

$t_b$  = the temperature of the standard buffer tube at the time of measurement,

$t_w$  = the temperature of the sea-water *in situ*,

$t'_w$  = the temperature of the sea-water sample at the time of measurement,

$a$  = a constant, individual for each indicator, showing the amount by which the dissociation exponent of the indicator varies for a temperature change of one degree in borax-boric acid buffer mixtures,

and  $\beta$  = another constant indicating the colour change of the indicator which takes place in sea-water ( $S = 34.5^\circ/\text{‰}$ ) with changing temperature.

Recently Brujewicz and Skopintzew (1933) reinvestigated the temperature effect on the colorimetric determination of pH in sea-water, and as a result of their investigation

\* It is interesting to note here that Miller (1934) pointed out that the pH values which he observed in the English Channel agreed with the findings of Seiwel (1928), but were lower than the values observed by Atkins (1922). Similarly, the values observed by Miller (1934) in the tropical regions of the Atlantic and Pacific Oceans were in general lower than those found by Mayer (1922). Both Atkins and Mayer used McClendon's buffer standards and applied McClendon's smaller salt-error corrections.



they proposed an equation which resembles in form that of Buch. Their equation is as follows :

$$\text{pH}_w = \text{pH}_b + a (t_b - t'_w) - \gamma (t'_w - t_w)$$

where  $\text{pH}_w$ ,  $\text{pH}_b$ ,  $t_b$ ,  $t_w$ ,  $t'_w$  and  $a$  have the same indications as in Buch's equation, and  $\gamma$  is the temperature coefficient of the real (not the visual) change of pH of sea-water.

Both equations give practically concordant results. Brujewicz and Skopintzew's equation was, however, employed in correcting our observations for the temperature effect, since the data of these authors furnish values of the constants of the above equation for each of the three indicators, which we used, at different pH values.\*

The first step in computing  $\text{pH}_w$  was to find out  $\text{pH}_b$ , the real pH of the matching standard buffer tube at the temperature of measurement. Brujewicz and Karpova (1933) investigated the temperature coefficient of the pH changes in Palitzsch borax-boric acid buffer mixtures and gave a table showing by how many pH units the inscription on the standard buffer tube, referring to a temperature of 18° C., would need to be corrected in order to give the real pH of the buffer tube at the actual temperature of measurement, *i. e.*  $\text{pH}_b$ . This correction is occasionally referred to in the literature as the Walbaum correction (Cooper, 1933a). Since, however, the calibration temperature of McClendon buffer mixtures, which we used, was 20° C., and as one has good reason to assume that the sensitiveness of McClendon borax-boric acid buffer mixtures would be very similar to that of Palitzsch buffer mixtures, the table given by Brujewicz and Karpova was reconstructed so as to refer to a calibration temperature of 20° C. instead of to that of 18° C.

All the observed values of pH were then corrected for the temperature effect, using the equation of Brujewicz and Skopintzew, and in this way values of  $\text{pH}_w$  were obtained.

#### THE EFFECT OF PRESSURE ON pH.

It is well known that the hydrogen-ion concentration in a sea-water sample is inter-related to its carbonic acid equilibrium. When a sea-water sample is brought up to the surface from a great depth its carbonic acid equilibrium is displaced as the pressure is diminished, and the volume of the sample is consequently increased. Buch and Gripenberg (1932), who investigated the effect of pressure on this equilibrium, give a table showing the magnitude of  $\Delta \text{pH}$  to be subtracted from the pH value measured at the surface for an increase of depth of 1000 m. That table shows that the change in pH with depth is considerable, and that the difference,  $\Delta \text{pH}$ , between pH at the surface and pH at a given depth, varies with pH.

If the present observations were further corrected for the pressure effect they would give the actual pH of the water *in situ*. But since the primary aim has been to present the observations in a form comparable with other modern data of pH, which are corrected only for salt and temperature effects, the correction for the pressure effect has not been made. This effect can be easily corrected by the use of Buch and Gripenberg's table. Further, I have based the description and discussion of the pH distributions not on the pH of the water *in situ*, but on the pH which the water would attain when raised to the surface, *i. e.* on the pH of the water at its temperature *in situ* but under atmospheric pressure. Presented in such a form (which is analogous to the "potential temperature"

\* More recently Buch (1937) himself has recommended the use of Brujewicz and Skopintzew's equation for the correction of the temperature effect on the colorimetric measurements of pH.



—an important notion introduced into oceanography by Helland-Hansen), the pH observations afford a means for following the movement of an individual mass of water, for it remains practically constant (if mixing, photosynthetic and geochemical processes be excluded), whereas the pH *in situ* would change as soon as the water mass moves to a different level.

#### ORDER IN WHICH CORRECTIONS HAVE BEEN APPLIED AND PRESENTATION OF DATA.

In determining the constants of their equation for the temperature effect on the colorimetric measurements of pH, Brujewicz and Skopintzew used pH values which were not corrected for the salt effect. Our observed values of pH were therefore corrected first for the temperature effect, and the values of  $pH_w$  so obtained were then corrected for the salt effect. In this way the pH of sea-water at its temperature *in situ*, corrected for salt-error and measured under atmospheric pressure, was obtained. This value, which should be properly designated as  $pH_t$ , will be presented simply as pH in the text and in the Tables of pH Data (Column 3).\*

The values of  $pH_w$  were also reduced to 0° C. and then corrected for the salt effect, and values of  $pH_o$  were thus obtained (Column 4). Reduction of pH observations to such a standard temperature as 0° C. would not only allow of comparison of pH observations amongst themselves (Cooper, 1933*a*), but also of an easy comparison with the observations of other investigators on the waters of the same region or of different regions, which is always highly desirable. Further, in order to allow our observations to be compared with other observations, which had been corrected only for the salt effect and recorded in the literature, they have been similarly corrected for salt-error only and the corrected values are entered in the Tables of Data (Column 2).

#### ACCURACY OF RESULTS.

As the interval between successive tubes in our buffer scale is 0.02 pH unit, our observations are accurate to  $\pm 0.01$  pH. They are in very close agreement with the observations made by Miller (1934) in the same area. The average pH of 13 surface observations which he made between Colombo and Mombasa is 8.13, measured at an average temperature of 26.6° C.; the average pH of 15 surface observations which we made between Mombasa and Colombo is 8.12, measured at an average temperature of 29.6° C. Both sets of observations were corrected for salt-error. Miller's measurements were made by a different colorimetric method with a different salt-error and were checked electrometrically. Our observations on the surface waters near the equator are also in close agreement with similar observations made by the "Meteor" in the tropical Atlantic regions. We must, however, bear in mind that colorimetric measurements are subject to certain errors, such as those due to eye-strain, non-uniformity of light, etc. We have therefore checked all our observations graphically, station by station, and, in certain doubtful cases, mutually with corresponding hydrographic data. This process rendered 1–2% of the total number of observations most probably incorrect and they were discarded. Missing values were found by graphical interpolation.

As to the absolute value of our observations the following general remarks on

\* These Tables of Data are preserved in the Library of the British Museum (Nat. Hist.), where they are available for reference.

measurements of pH may help to show how far or near these measurements are from absolute correctness.

There is much confusion in the literature regarding the real significance of pH. When Sørensen carried out his work on the determination of hydrogen-ion concentration, the modern theory of strong electrolytes had not been developed, and, of course, his measurement and calculation of hydrogen-ion concentration were based on the classical theory of Arrhenius (1899), which postulated incomplete dissociation of strong electrolytes in aqueous solutions. According to the modern theory, dilute aqueous solutions of strong electrolytes are completely dissociated into ions and the results arrived at by conductivity determinations and by osmotic or electrometric measurements, which have been interpreted as indicating incomplete dissociation of the electrolyte, have their natural explanation when the interionic forces acting between the electrically-charged ions are taken into consideration.

Owing to these interionic forces, the active mass of an ion, its activity ( $a$ ), cannot be taken as equal to its concentration  $C$ , the proper equation for these quantities being :

$$a = f_a \cdot C$$

where  $f_a$ , termed the activity coefficient, differs for the different ions, and varies for the individual ion with the nature and concentration of the other ions present. In the light of this conception a distinction should be made between the total hydrogen-ion concentration and the activity of hydrogen ions. For instance, the concentration of hydrogen ions in 0.01 NHCl is equal to the total concentration of the acid, hence  $[H] = 0.01$ . The activity of hydrogen ions is smaller and equal to  $f_H \times 0.01$  where  $f_H$  represents the activity coefficient of hydrogen ions in 0.01 NHCl. We may represent this activity by  $[aH]$ . Similarly we can represent the negative logarithm of hydrogen-ion concentration and its activity by pH and  $paH$  respectively.

Now in electrometric measurements it is the activity of hydrogen ions which determines the potential and it is actually the  $paH$  which is derived from these measurements. Since Sørensen computed his pH values (also pH values of buffer mixtures in common use) on the basis of the classical dissociation theory, whereas the new computations are based on the modern theory of strong electrolytes, it is obvious that the original notation of hydrogen-ion concentration (Sørensen pH) has no real meaning.

To clear up this confusion Kolthoff (1930) has proposed to assign to  $[H]$  and pH the significance they have according to the modern theory of strong electrolytes, and to express the corresponding activity and activity exponent by  $[aH]$  and  $paH$ . Values obtained on the basis of Sørensen's original work should be indicated by the Sørensen value  $[sH]$  and the Sørensen exponent by  $psH$ .

However, as most of the work which has been done in the past on the determination of hydrogen-ion concentration (hydrogen-ion concentrations of buffer mixtures, etc.) is expressed in Sørensen units, it seems better, mainly to avoid confusion, to adhere to them, though they have no actual significance. As soon as the difference between Sørensen  $psH$  and  $paH$  is fixed by international agreement it would be easy to transfer all  $psH$  values into  $paH$ .

It should therefore be understood that the pH values recorded in this report are really Sørensen values ( $psH$ ), in spite of the fact that they are expressed as pH for simplicity. It would be a wide step in chemical oceanography if one rule could be observed in calculating and in publishing the hydrogen-ion measurements.



## DISTRIBUTION.

The distribution of hydrogen-ion concentration in the north-western Indian Ocean and its adjoining gulfs will be dealt with under the following headings :

- (1) Vertical distribution,
- (2) Horizontal distribution,
- (3) Discussion of distributions,

with reference to the origins and relationships of the different water masses.

Both description and discussion of distributions will be based on the value which the pH *in situ* would attain when the water sample is raised to the surface. As already mentioned in a previous section, this value is simply referred to in the text as pH and not as  $pH_t$ .

## VERTICAL DISTRIBUTION.

In vertical section we recognize in the distribution of pH in the north-western Indian Ocean a general fundamental type valid for the entire area of investigation. In certain regions this type may, however, be modified into subordinate types by local conditions, currents, or seasonal changes.

The outstanding features of this general type are as follows. Throughout the north-western Indian Ocean the highest values of pH occur, as a rule, in the more or less homogeneous surface waters overlying the thermocline. With increasing depth the pH decreases until it reaches a minimum value in mid-depths. The depth at which the minimum value of pH occurs varies from one region to another, and in certain regions it varies with the season. With further increase of depth there is a constant, sharp or gradual, increase in pH until it reaches a relatively high value at the greatest depth sampled. However, over the southern end of the Red Sea, in the Gulf of Aden and its approaches, and in the Gulf of Oman the occurrence of secondary maxima and minima is not unusual, though less frequent in the open ocean.

These general features are illustrated by a series of selected pH-depth curves (Text-fig. 2).

The highest surface pH value met with in our area of investigation ( $pH = 8.16$ ) occurs at Station 93, in the central Arabian Sea, and the lowest surface pH value ( $pH = 7.91$ ) occurs at Station 49, off Ras Madraka on the South Arabian coast. The usual range of surface pH is, however, 8.02–8.13.

The minimum value of pH occurring at mid-depths ( $pH = 7.56$ ) is found at Station 12, which lies on the northern side of the Gulf of Aden at its western end. The usual range of minimum pH values is, however, 7.66–7.80.

The highest pH value occurring at great depths ( $pH = 8.18$ ) is found at a depth of 4000 m. at Station 167.

As the upper limit of the range of minimum pH values is in general 7.80, and in order to bring to light the regional differences of vertical distribution, the whole water column in a vertical profile will be divided, for convenience of description, into three main pH layers—an upper layer with higher values of pH, a mid-layer with low values, and a lower layer with relatively high values of pH as defined by the position of the 7.80 isolines. At stations where there are more than two 7.80 isolines in a vertical profile, the division of



the water column into layers will be modified accordingly. It should be borne in mind, however, that in the actual description of a vertical profile the pH vertical gradient—which, for convenience, will be defined as the number of pH units per 100 m. difference of depth—at any part of the water column will be taken into consideration as well. Thus, the lower boundary of the surface layer will be taken as the level at which the pH vertical gradient is greatest in the upper part of the water column.

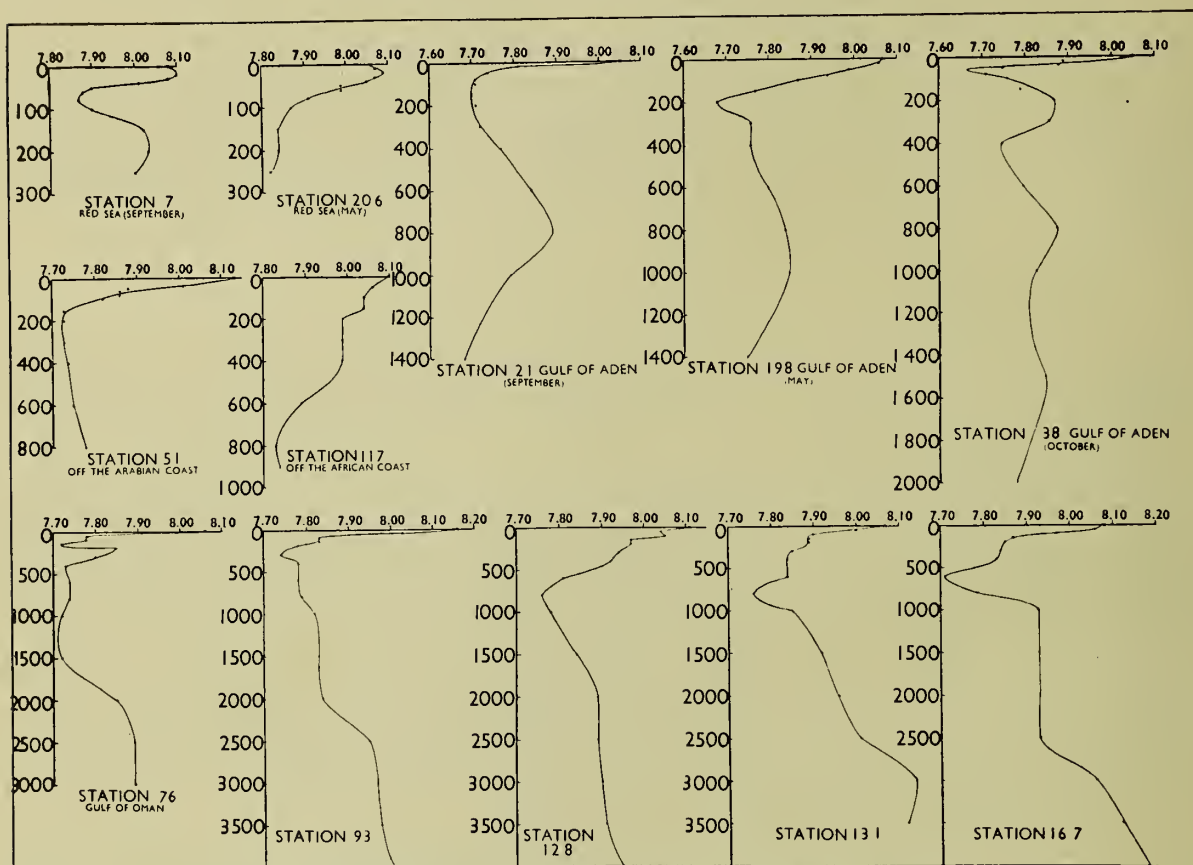


FIG. 2.—ILLUSTRATING THE VARIOUS TYPES OF pH-DEPTH CURVES.

*Vertical profiles.*—The vertical profiles of pH in all sections (Sections A–M) along the southern end of the Red Sea, across the Gulf of Aden, in the Gulf of Oman, in the Arabian Sea and the north-western Indian Ocean are shown in detail in Text-figs. 3–22. The profiles make no allowance for the fact that owing to stress of weather and currents the stations did not fall always along a straight line. The bottom relief is based on the topographical results of the present Expedition (Farquharson, 1936). The stations constituting a section are in all cases indicated by numbers above each profile. The isolines are drawn at intervals of only 0.05 pH in order to avoid the figures being crowded by lines, though the accuracy of our measurements is much greater.

#### THE SOUTHERN END OF THE RED SEA.

*Section A: Conditions at the end of the summer season (September) (Text-fig. 3).*—Observations of pH were made at three stations (7, 8 and 9) along Section A in September. Over this southern end of the Red Sea the surface pH is high and uniform, as it varies only

from 8.08 to 8.10. Since the pH of sea-water is dependent upon the equilibrium conditions of the carbonic acid system, this high pH is obviously due to the phytoplanktonic activity

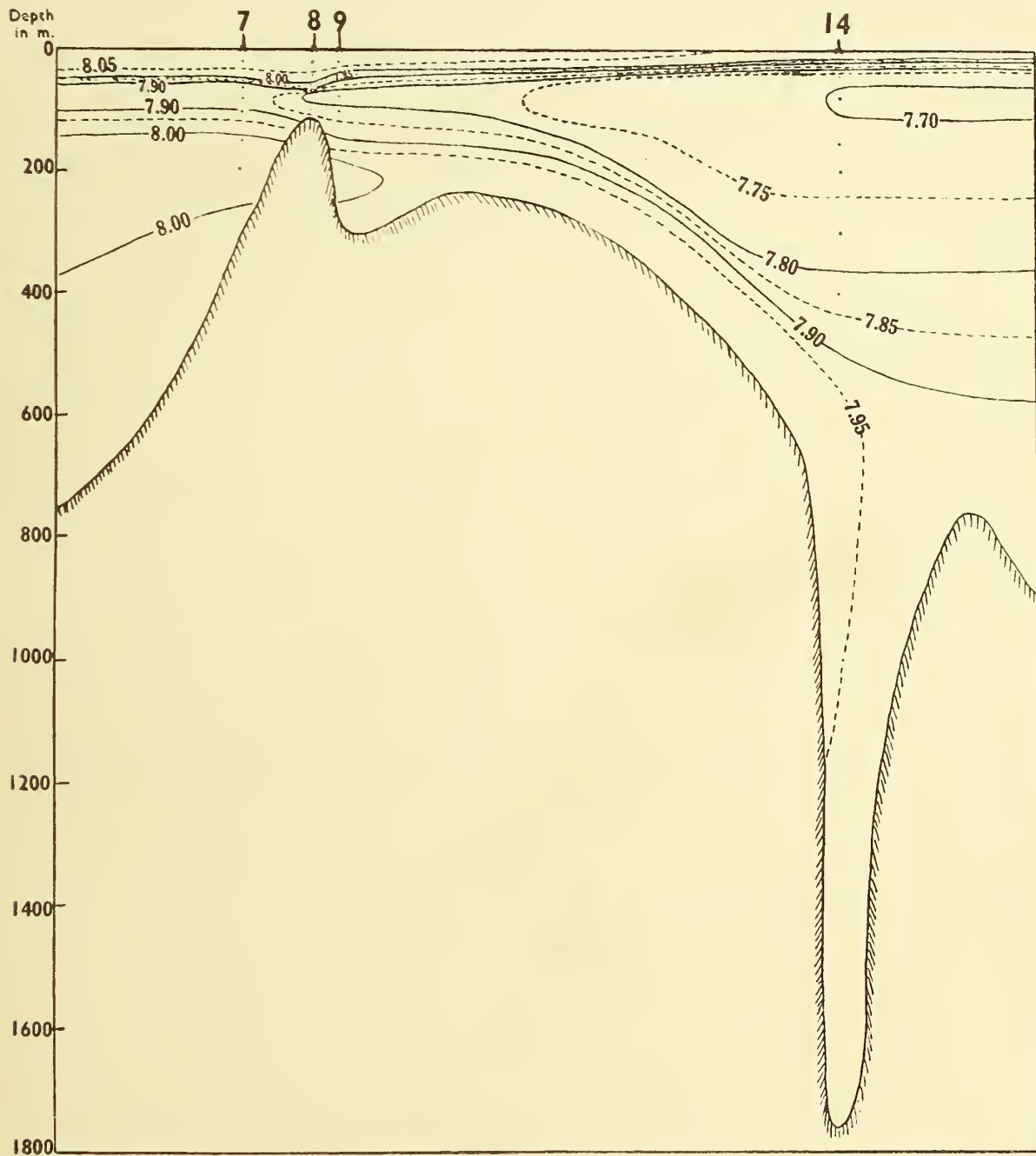


FIG. 3.—THE DISTRIBUTION OF pH ALONG SECTION A IN THE SOUTHERN END OF THE RED SEA AND THROUGH THE STRAITS OF BAB-EL-MANDEB (SEPTEMBER).

which reduces the carbon dioxide content of the surface waters, thus causing the pH to rise.

As is seen from the Tables of pH Data (Stations 7, 8 and 9) the maximum pH of the

surface waters does not occur usually at the surface, but at a depth of 20 m. This fact indicates that, in so far as the phytoplanktonic activity is reflected by pH vertical distribution, the maximum phytoplanktonic activity does not necessarily take place at the very surface of the sea, but just below it. A possible explanation of this is that the light is often too intense at the surface (Marshall and Orr, 1928), so that the zone of maximum phytoplanktonic activity lies well below the surface.

Descending below the surface, the pH remains constant or changes slightly until a depth of 30 m. is reached, below which it drops rapidly with increasing depth, until it reaches a minimum value at a depth of 80 m. This minimum value varies from 7.87 at the northerly station to 7.78 at the southerly one. This rapid decrease in pH will shortly be shown to be due to the influence of an inflowing current from the Gulf of Aden characterized by low pH values. Below the depth of minimum value the pH rises with increase of depth until it attains a secondary maximum value (8.02–8.03) at a depth of 200 m. Below this depth the pH falls to a value of 8.00 in the vicinity of the bottom. At Station 8, which is the shallowest on the section, the pH attains, however, a value of only 7.84 near the bottom, but such is the pH value characteristic of similar depths in the neighbourhood.

The greatest pH vertical gradient (pH units per 100 m. difference of depth) amounts to 1.10 pH units and occurs at Station 7 between the depths of 40 and 50 m. and at Station 9 between the depths of 30 and 40 m.

The conditions along this section as a whole are graphically represented in Text-fig. 3 on the left-hand side. From a pH standpoint we can distinguish at least three water strata over the southern end of the Red Sea at the end of the summer season: An upper stratum with a high pH and extending from the surface down to a depth of about 60 m.; a mid-stratum with lower values of pH and exhibiting a minimum at a depth of 80 m.; and finally a lower stratum with relatively high values of pH which extends to the bottom. The course of pH isolines through the Straits of Bab-el-Mandeb throws abundant light on the origin and movement of these three water masses, which will be considered in the following section.

*The water movements in the Straits of Bab-el-Mandeb at the end of the summer season (September).*—Section A (Text-fig. 3) is extended to include Station 14, lying in the western end of the Gulf of Aden, in order to bring out the conditions in the Straits of Bab-el-Mandeb in September. At this time of the year the vertical profile shows clearly the inflow of a massive sub-surface current, characterized by low pH values (7.80 and less), from the Gulf of Aden into the Red Sea. This inflow serves as a compensation for the water loss from the Red Sea due to excessive evaporation during the summer months. It is also seen that this inflowing water mass constitutes the bulk of the water column in the Straits at the time of observation. As the maximum inflow probably sets in at a time later than that of maximum evaporation, it is reasonable to assume that the inflow reaches its greatest intensity in September. The minimum value of pH within this inflowing water mass is as low as 7.70 at Station 14 in the Gulf of Aden, but it rises to 7.79 over the sill near Great Hanish Island, and to 7.87 at Station 7. It is thus seen that the pH of this water mass increases as it passes through the Straits into the Red Sea, presumably through mixing with Red Sea water in the neighbourhood of the sill.

The deep layer with relatively high pH values is seen in the profile to flow as a bottom current out of the Red Sea. The curved course of the 8.00 isoline indicates that this



bottom current, after passing for a short distance over the sill, turns back into the Red Sea. Such a course is probably taken by the current in view of the combined resistance offered against it by the obstruction of the sill and the great volume of the inflowing current. It should, however, be noted that it is possible that this turning back of the Red Sea bottom current may not be a permanent feature and it is likely that this current is at times overcome by the ingoing tidal current. The water which succeeds in passing over the sill into the Gulf of Aden pours partly—owing to the sudden increase in depth at Station 14—into the deep gully, as shown by the course of the 7.95 isoline, which is seen in the profile to be filled with water having a relatively high pH, and partly runs, as shown by the course of the lower 7.90 isoline, into the general depths of the Gulf of Aden. Had we taken reliable pH observations north of Station 7 we might have been in a better position to trace the origin of this bottom water further north in the Red Sea.

The *régime* of surface currents in the Straits is determined mainly by the prevailing winds, but is influenced to a lesser degree by the tidal streams. At the time of observation the direction of the wind (N.N.W.–N.W.) was such that a wind-driven current flows out of the Red Sea into the Gulf of Aden. The course and trend of the isolines within the surface layer also bear out this impression, but it should be borne in mind that, though Mayer (1919) pointed out that surface currents could be detected from pH observations, on account of planktonic activity in the surface layer which ensues with different intensities at different times, conclusions regarding surface currents from pH observations should be made with great caution.

It is thus seen that the distribution of pH in the Straits of Bab-el-Mandeb in September is determined mainly by the *régime* of currents in the Straits at that time. Similar conclusions regarding the water movements in the Straits of Bab-el-Mandeb have been reached by Vercelli (1931) from the hydrographical observations and direct current measurements of the “Amiraglio Magnaghi” in July, 1929, and by Sewell (1934) in a preliminary treatment of the temperature and halogen-content observations of the present Expedition. This shows that from pH observations, which have been properly corrected and reduced, it has been possible to follow and trace the water movements in the Straits of Bab-el-Mandeb. The usefulness of pH observations in the study of such water movements is further borne out by the interesting fact that, when the average properties of the three water strata passing through the Straits are compared, the intermediate character of the mid-stratum shows itself in other properties, such as temperature, salinity and oxygen-content, as well as in pH.

*Section A: Conditions at the end of the winter season (May).*—Observations were repeated on the return journey during May along Section A at the same three stations of the summer season, the stations are now listed as 206, 204 and 203, and further observations were taken at Station 208, which lies north of Station 206.

At the end of the winter season the pH-depth curve in the southern end of the Red Sea presents a marked contrast to what it was at the end of the summer season in that it does not exhibit a minimum at mid depths, the minimum pH value occurring at the maximum depth samples (Text-fig. 2, Station 206).

The surface pH varies from 8.06 to 8.10 (see Tables of pH Data) and, as is better shown by comparing the value of  $pH_o$ , it tends to be now lower than it was in the previous season. The maximum pH occurs again almost always below the surface at a depth of 10–20 m., indicating that the maximum phytoplanktonic activity takes place, as in the previous

season, below the surface. The pH vertical gradient is, on the whole, smaller than it was at the end of the summer season.

The vertical distribution of pH along Section A, as a whole, is represented in Text-fig. 4 on the left-hand side. This profile gives now a different picture of pH distribution and a comparison with the summer profile shows that from a pH standpoint only two layers can be distinguished over the southern end of the Red Sea in May. The separating boundary between these two layers is marked by a distinct pH vertical gradient. The pH of the deep layer is now much lower (7.82–7.95) than it was in September (8.00–8.03), and that of the surface layer, as already pointed out, is also lower.

*Seasonal changes.*—The cause of these seasonal changes in pH over the southern end of the Red Sea should be sought in the change of hydrographic conditions from the one season to the other as well as, so far as the surface layer is involved, in the variation of the rate of biological activity. A comparison of hydrographic conditions of the surface waters in September and May shows that the surface temperature over the southern end of the Red Sea was about 4° C. lower in May than it had been in September. The lowered temperature of the surface waters in May tends to increase the capacity of the surface to absorb carbon dioxide from the atmosphere and probably to make the photosynthetic processes slower. Since the pH of sea-water is determined by the equilibrium conditions of the carbonic acid system, this combined effect of temperature accounts for the low pH of the surface in the winter season.

The low pH values of the deep layer and its homogeneity, as shown by its small and uniform pH vertical gradient, suggest that this water-mass has been formed, in accordance with one of the fundamental conceptions of oceanic circulation, at the surface somewhere during the winter months, and it is reasonable to presume that it has its origin further north in the Red Sea. The low temperature of the surface in the northern regions of the Red Sea during winter increases the density of the surface water and causes it to sink.

The distinct pH vertical gradients existing between the surface layer and the water below it are due to the fact that winter conditions are disappearing and that the heating of the surface waters has already begun, giving rise to the formation of the ill-defined but recognizable boundary surface.

*The water movements in the Straits of Bab-el-Mandeb at the end of the winter season (May).*—Section A has been drawn to include Station 200 at the western end of the Gulf of Aden and thus to bring out the conditions in the Straits of Bab-el-Mandeb in May (Text-fig. 4).

The vertical distribution of pH in the profile of this section reveals several interesting points regarding the water movements through the Straits of Bab-el-Mandeb in May. It is seen that Red Sea water from mid and great depths flows out as a deep current into the Gulf of Aden. In the Straits the greater part of the water column consists now of this Red Sea water. The course of the 7.83 isoline north of the sill indicates an upward movement of the Red Sea deep water as it approaches the sill. This upward movement of the current pushes its water over the sill into the Gulf of Aden. The course of the isolines south of the sill indicates the subsequent history of this current. The greater portion of it pours down into the deep gully lying in the position of Station 200 and at the same time flows further into the general depths of the Gulf, with a nucleus at about 500 m. This deep Red Sea current, characterized by its deep course and somewhat high pH values, will be traced further in the Gulf of Aden in describing Sections B, C and D.



The direction of the wind at the time of observation (E.-E.S.E.) was such that a surface wind-driven current would flow from the Gulf of Aden into the Red Sea, and the course of the 8.10 isoline also gives this impression.

We come, therefore, to the conclusion that in May there pass through the Straits of Bab-el-Mandeb a deep current which flows out of the Red Sea into the Gulf of Aden and

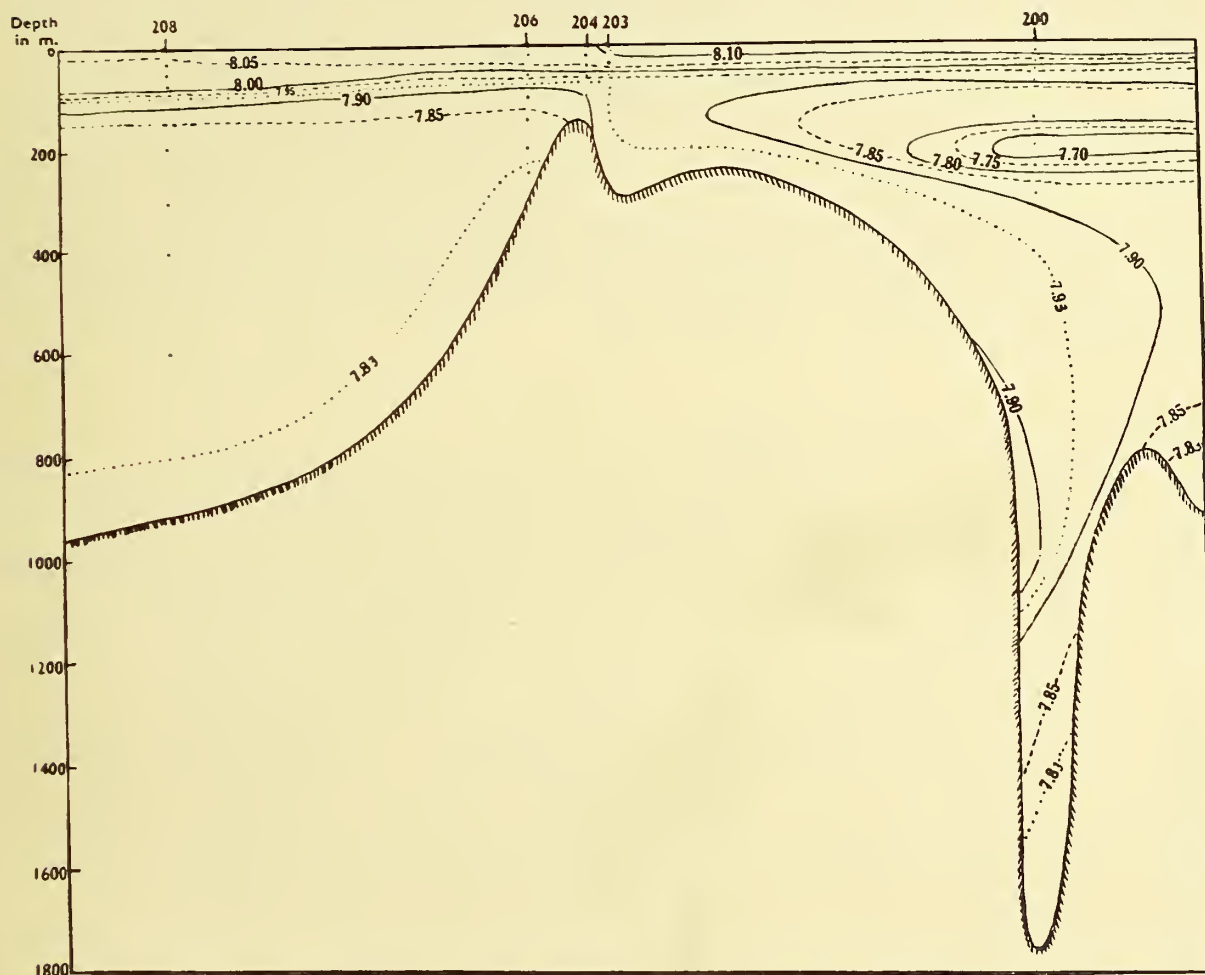


FIG. 4.—THE DISTRIBUTION OF pH ALONG SECTION A IN THE SOUTHERN END OF THE RED SEA AND THROUGH THE STRAITS OF BAB-EL-MANDEB (MAY).

constitutes the bulk of the water column in the Straits, and a surface current which flows into the Red Sea.

The much reduced sub-surface current, characterized by low pH values (7.80 and less), which was flowing into the Red Sea during September now hardly reaches the entrance of the Straits. It has even failed to drive back an upper band of the Red Sea deep current which eventually finds its way into the Gulf of Aden below the surface layer. The somewhat high pH value, which is higher than that of the surrounding water below and above it, found at a depth of 150 m. at Station 200, signifies the existence of this band of Red Sea water there. Owing to its small volume it is bound to lose its marked character before it travels far in the Gulf of Aden.



Before passing on to describe conditions along Section B, the interruption of the 7.90, 7.85 and 7.83 isolines at the sill calls for some comment. The interruption of the 7.90 isoline at the sill might be explained as due to vertical oscillations, which have been reported by Vercelli (1927) from this region and which result in thermo-haline oscillations, connected with the rhythm of the tide. However, to explain the interruption of the deeply situated 7.85 and 7.83 isolines on similar grounds seems inadequate, as it is hardly thinkable that vertical oscillations would extend to such great depths. This raises the question whether the deep water below 1000 m. in the gully has originated from Red Sea bottom water or from another source, presumably a mixture of mid and deep (not bottom) water from the Red Sea with another current, with low pH values, moving westwards along the bottom in the Gulf of Aden. In all probability the latter view seems sounder, and that is why the portions of the 7.85 and 7.83 isolines in the gully have been drawn to demonstrate this probability. This leads us to the conclusion that, pending the correctness of our view as to the origin of the water in the depths of the gully, the bottom water of the Red Sea is not involved to any great extent in the water-exchange through the Straits of Bab-el-Mandeb in May.

#### THE GULF OF ADEN AND ITS APPROACHES.

Observations of pH along three sections B, C and D, running across the Gulf of Aden were made in September–October and were later repeated in May. Section B runs across the extreme western end of the Gulf, Section C runs between Aden and Berbera and Section D across the mouth of the Gulf at its eastern end. Observations along Section E, which runs through Socotra Channel were also made in October and were repeated in May. The pH distribution along each of these sections will be considered separately.

*Section B: Conditions in September* (Text-fig. 5).—Observations of pH along section B were made at three stations (12, 13 and 14) in September. Over this end of the Gulf the pH of the surface waters varies from 8.02 to 8.06. Below the surface the pH decreases suddenly to a minimum value of 7.56 at the shallow depth of 20 m. at Station 12, which lies on the Arabian side of the Gulf. This pH value is the lowest which we met in our area of investigation. At the other two stations on the section the minimum pH value amounts to 7.70 and occurs at lower levels. With increasing depth the pH increases till it reaches a value varying from 7.83 near the bottom in the northern side of the Gulf to 7.95–7.98 in the deep gully lying below Station 14.

The general arrangement of the water strata in the profile of this section is very similar to that found in the Straits of Bab-el-Mandeb in the month of September. One outstanding feature is the thickness of the layer with minimum values of pH (less than 7.80) which constitutes the greater part of the water column over the general depths of the Gulf. The cause of these low pH values within this layer must be sought in the hydrographic conditions at the time of observations. Examination of the temperature observations reveals at once the presence of a well-developed temperature gradient (and consequently a density gradient) near the surface along this section. The presence of such a sharp boundary between the layer under consideration and the surface layer prevents mixing across the boundary and makes the former dependent for its oxygen supply on lateral exchanges, thus leaving it in a state of relative stagnation. This layer becomes therefore a seat of organic oxidations, carbon dioxide being set free, and the pH is

consequently lowered. One fact, which strengthens this explanation is that the reduction in oxygen-content, as shown by the present Expedition data, stands in close correspondence

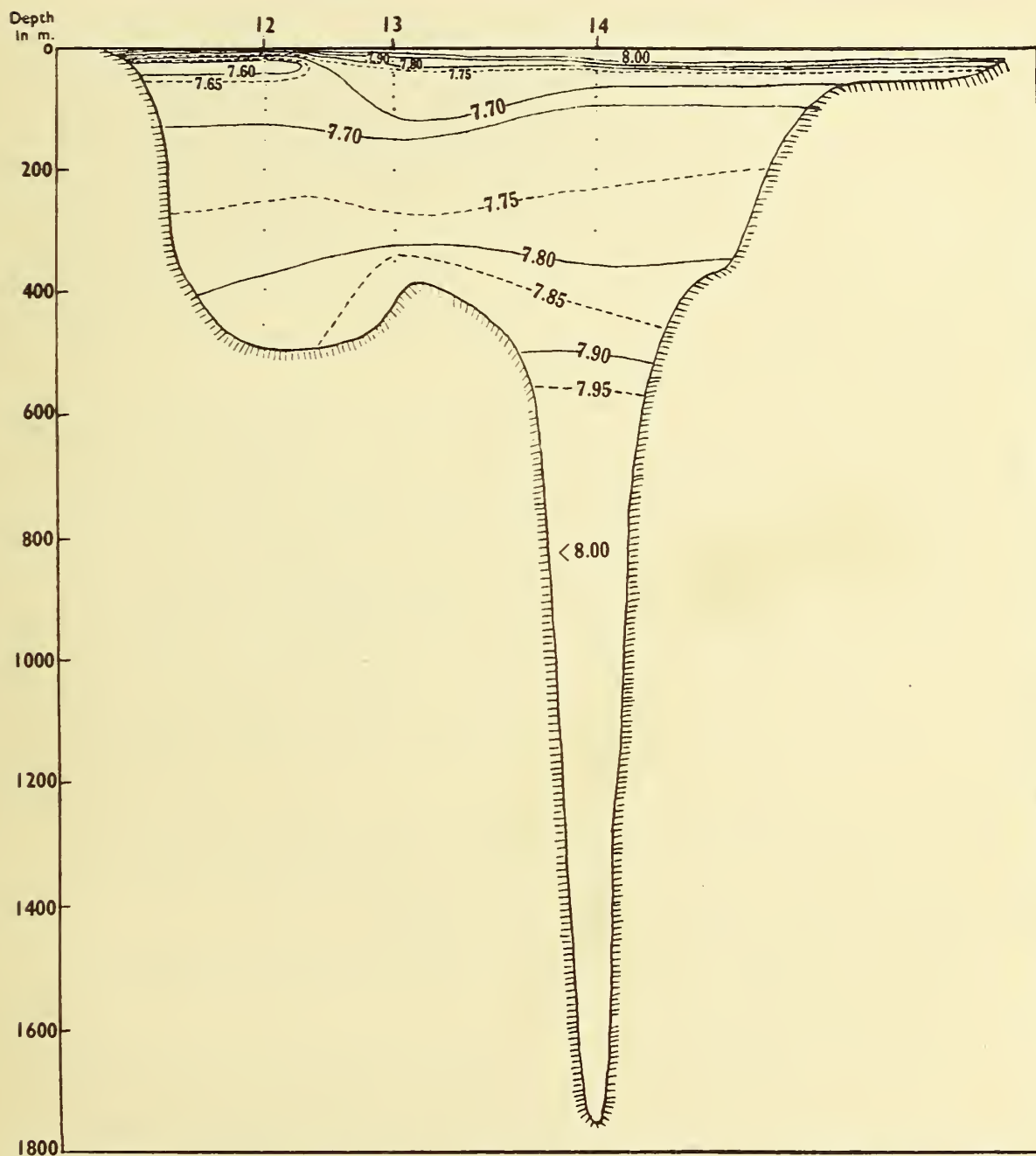


FIG. 5.—THE DISTRIBUTION OF pH ALONG SECTION B ACROSS THE WESTERN END OF THE GULF OF ADEN (SEPTEMBER).

with the decrease in pH. Moreover, the presence of a well-developed density gradient near the surface causes the decay of sinking organic *débris* (of similar specific gravity) to occur at a higher horizontal level and this results in an increase in the vertical thickness of the minimum pH layer. The upper and lower boundaries of this minimum pH layer

(upper and lower 7.80 isolines) give thus the approximate limits to which most of the organic oxidations occurring in the sea are confined.

The cause of the very low pH (7.56) observed at the shallow depth of 20 m. at Station 12 is, however, not clear. Judging by the order of magnitude of low pH values found in other regions of the Arabian Sea, where more intense oxidation is known to be taking place, the occurrence of this low pH value cannot be entirely explained on oxidation grounds. When we examine the temperature observations we find that the surface temperature (23.46° C.) at this station is the lowest surface temperature observed at any of our stations in the Gulf of Aden. Moreover, we find that whereas the magnitude of the maximum pH vertical gradient at Stations 13 and 14 corresponds well with the magnitude and trend of the maximum vertical temperature gradient, it is much higher at Station 12 than one would expect from the temperature gradient. Although these facts do not throw much light on the cause of the abnormally low value of pH, they suggest that conditions at Station 12 were disturbed somehow by an unknown agency, such as an influx of fresh water from the Arabian coast.

The minimum pH layer is sharply separated from the surface layer, which is very thin at this time of the year, by a well-developed vertical pH gradient. The steepest gradient occurs between the depths of 10 and 20 m., where it amounts to 3.7 pH units and is by far the largest gradient found in our area of investigation. At Station 13 it is 1.7 units and at Station 14 it is 2.9 units and it occurs at a lower level, namely, between 30 and 40 m. It is interesting to note that the greatest vertical temperature gradients occur at the same levels as the greatest pH gradients. This simultaneous development of very pronounced vertical gradients of pH and temperature at the same levels suggests that in the Gulf of Aden the depth of the surface layer as a seat of phytoplanktonic activity is restricted in September by the sharp thermocline. Further, the presence of a well-developed density gradient near the surface cuts off the rich supply of nutrient salts stored in the deep water from the surface waters and consequently the phytoplanktonic activity becomes confined to a very thin layer.

In the deeper water below the minimum pH layer the values of pH are relatively high; the origin of this water has already been shown to be the Red Sea bottom current. The course taken by the isolines within this deep water indicates that the Red Sea bottom current flows out along the African coast in large volumes.

*Section B: Conditions in May* (Text-fig. 6).—On the homeward journey observations were repeated along Section B at the same three stations of the previous season; the stations are now known as 202, 201 and 200.

The surface pH varies from 8.05 on the Arabian side of the Gulf to 8.14 on its African side. The maximum pH throughout this section occurs invariably at a depth of 10–20 m.; the occurrence of the zone of maximum phytoplanktonic activity below the surface and not at the surface has already been explained as being possibly due to the strong light at the surface. Below this peak the pH value decreases with depth until it reaches a minimum at a depth of 200 m., below which it increases again to a secondary maximum near the bottom at Stations 201 and 202. However, at Station 200, which lies over the deep gully, the pH decreases again to a secondary minimum in the vicinity of the bottom of the gully. Unfortunately, no observations were secured during the previous season from depths below 1000 m. in the gully, but it is not improbable that the pH-depth curve would exhibit a similar secondary minimum at depths greater than 1000 m.



In May, at the beginning of the summer, the heating-up of the surface has begun and the vertical pH gradients are distinct, although not steep, as they were in September at the end of the summer season.

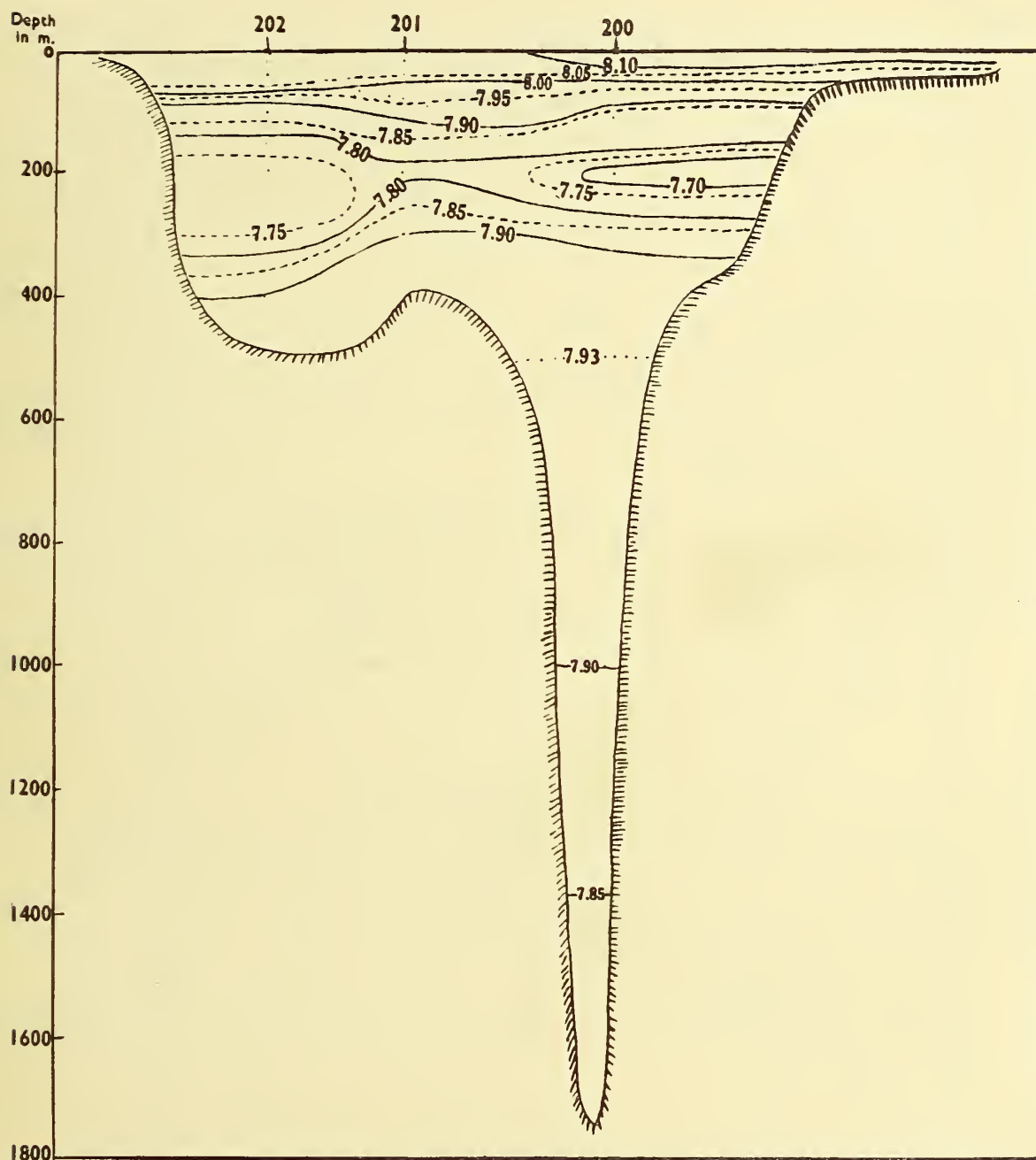


FIG. 6.—THE DISTRIBUTION OF pH ALONG SECTION B ACROSS THE WESTERN END OF THE GULF OF ADEN (MAY).

The average pH of the surface waters is, on the whole, higher than it was in September and the thickness of the surface layer is greater (50–90 m.). These facts indicate a higher phytoplanktonic activity, which can be explained as due to the deeper position of the thermocline at this season, the lower limit of the phytoplanktonic layer being consequently

pushed deeper. Moreover, since the density gradient is not yet steep enough to shut off the supply of nutrient salts from the surface waters, the activity of phytoplankton causes the pH to be higher. It is obvious that in May the zenith of this activity has already been passed.

Below the surface layer the minimum pH layer is seen to be much reduced in thickness. We have already seen, when describing Section A, that this mass of water failed to pass through the Straits of Bab-el-Mandeb into the Red Sea on account of the volume and flow of the Red Sea deep current. The pH distribution in this profile throws further light on the movement of this water mass. Opposed by the Red Sea deep current it is turned back and is seen in the profile as if moving in on one side of the Gulf and out on the other side. The volume of this mass is greater on the Arabian side (*ca.* 180 m.) than on the African side (*ca.* 100 m.) and has a nucleus at a higher level (at 200 m.) on the latter side than on the Arabian side (at 240 m.). Its small thickness on the African side, which is possibly due to mixing with Red Sea water possessing a relatively higher pH, and the higher level of its nucleus, which is apparently due to the upward thrust given to it by the projecting ridge lying in the position of Station 201, suggest that this was the out-flowing or eastward-moving portion of the mass, while its in-flowing or westward-moving portion lay on the Arabian side.

In the deep water below the minimum pH layer the pH is relatively high, and we have already traced the origin of this water to the outflowing Red Sea deep current. As seen from the profile, the volume of this water is, on the whole, much larger than in the corresponding profile for September. It now covers the great depths on the Arabian side, whereas in September there was hardly any Red Sea water there.

In the depths of the gully (below 1000 m.) the pH diminishes to a value of 7.82. We have already suggested (p. 140) that this decrease in pH is due to the westward drift of a low pH current on the bottom of the Gulf.

*Section C : Conditions in September* (Text-fig. 7).—Observations of pH at four stations (19, 20, 21 and 17) were taken along Section C in September.

The surface pH varies from 8.02 to 8.05; the maximum pH value of the surface water was frequently found more often at a depth of 10–20 m. than at the surface. Below this peak the pH decreases, at first suddenly and then gradually, until it reaches a primary minimum value of 7.68–7.72 at a depth varying from 40 to 200 m., but with further increase of depth the pH increases again until it attains a secondary maximum value of 7.84 on the Arabian side of the Gulf and of 7.94 on the African side at a depth of 600–800 m. Below the depth of secondary maximum the pH decreases again with depth until it reaches a secondary minimal value of 7.68–7.80 at great depths at all stations on this section except Station 17.

The levels at which the greatest vertical pH gradients occur lie between 10 and 40 m., and the values of the gradient vary between 2.2–2.9 pH units. The simultaneous development of steep pH and temperature gradients at the same levels strengthens the suggestion already made that the depth of the phytoplanktonic activity layer in September is restricted by the thermocline.

The vertical distribution of pH along this section is essentially the same as along Section B in September (*cf.* Text-figs. 5 and 7), but the profile of this section exhibits in a clearer manner four different water layers.

The surface layer, which varies in thickness from 10 to 40 m., is distinctly separated

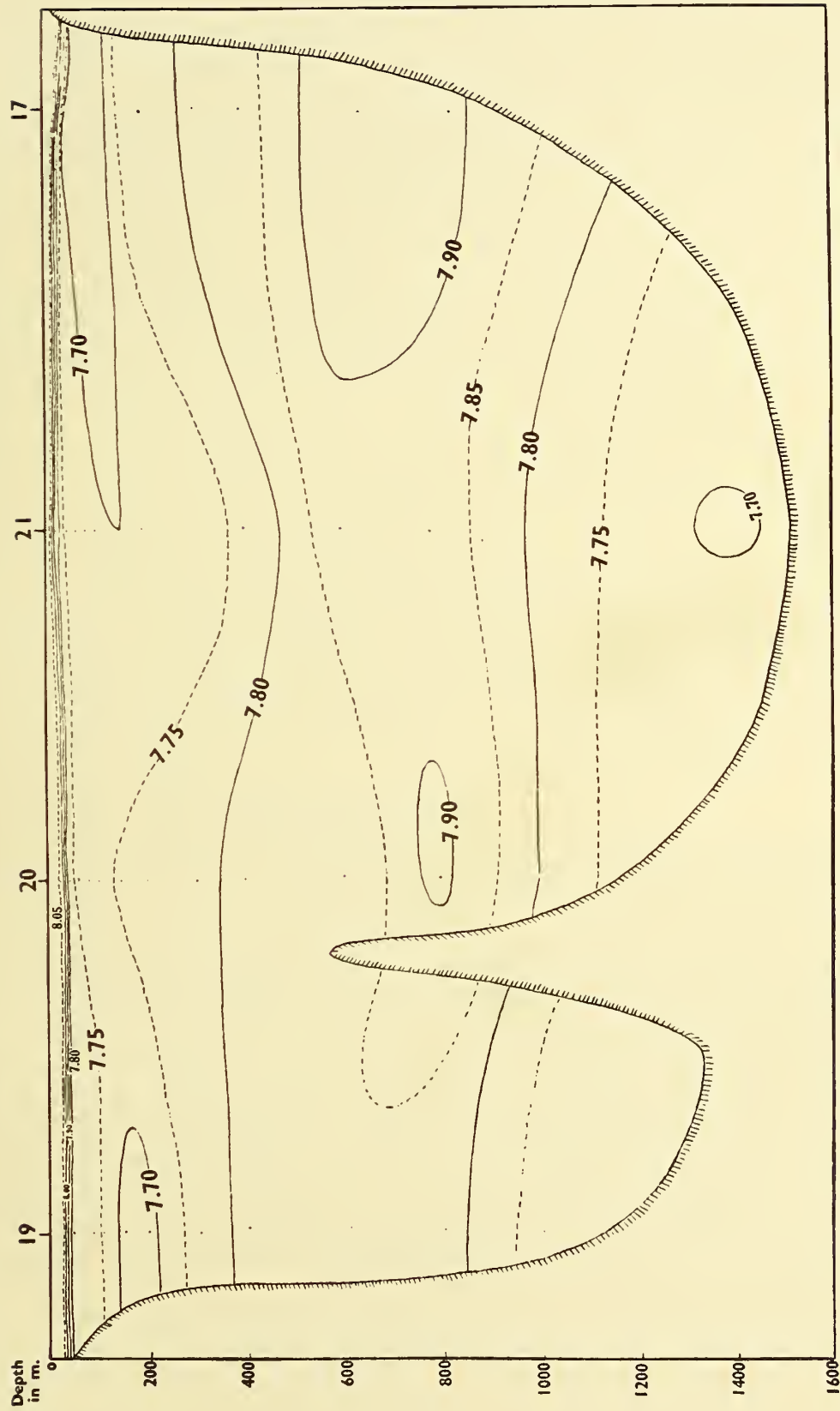


FIG. 7.—THE DISTRIBUTION OF pH ALONG SECTION C BETWEEN ADEN AND BERBERA (SEPTEMBER).



from the primary minimum pH layer by a well-developed vertical gradient. The latter layer represents the sub-surface current which flows through the Straits of Bab-el-Mandeb. The thickness of this layer is greatest at Station 21, and is greater on the Arabian side than on the African side. Its small thickness on the African side is probably due to mixing with the Red Sea bottom current, which flows out in large volumes along the African coast and possesses relatively higher pH values. We have already attributed the low values of pH within this layer to processes of organic oxidation due to relative stagnation.

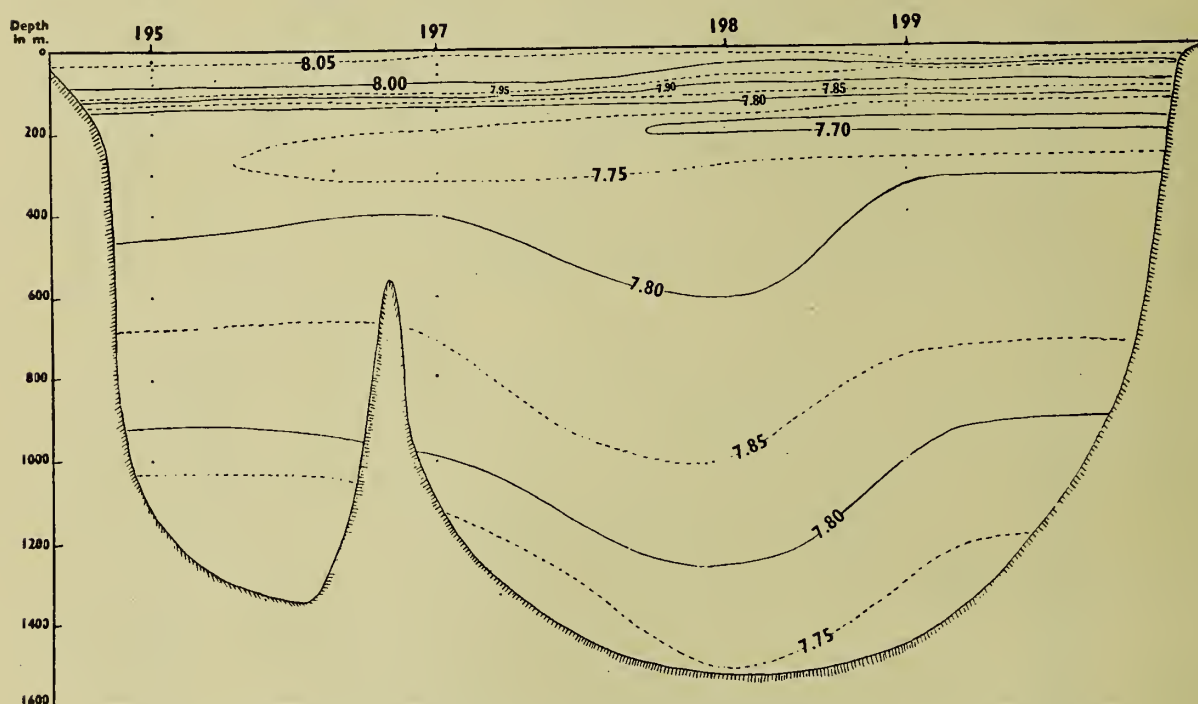


FIG. 8.—THE DISTRIBUTION OF pH ALONG SECTION C BETWEEN ADEN AND BERBERA (MAY).

Below the primary minimum pH layer is a tongue-shaped mass of water with an axis at about 700 m. and with a comparatively high pH. This mass represents the out-flowing bottom current from the Red Sea.

In the great depths of the Gulf we find a fourth mass of water with low pH values. From its temperature and salinity this water seems to have originated outside the Gulf and to represent a deep current from the Arabian Sea which finds its way into the Gulf of Aden and creeps westwards along its bottom. The low values of pH within this water are probably due to organic oxidations on account of its age and slow movement.

*Section C: Conditions in May* (Text-fig. 8).—Observations were repeated along Section C in May; the stations are now numbered 195, 197, 198 and 199. Station 199, however, does not coincide in position with Station 17.

The surface pH varies from 8.03 to 8.08; at some stations the maximum pH occurs again below the surface. The pH remains constant or changes slightly and gradually with increase of depth in the surface water. At a depth of 100–150 m. the pH falls, at first suddenly and then gradually, until it reaches a minimum value of 7.72–7.76 at a depth of 300 m. in the northern half of the Gulf and of 7.68–7.69 at a depth of 200 m. in

the southern half. Below the depth of this minimum value the pH increases with further increase of depth until it reaches a secondary maximum value of 7.84–7.68 at a depth of 800–1000 m. Below this the pH drops to a secondary minimum value of 7.73–7.76 near the bottom. At Station 197, however, observations were not taken near enough to the bottom to demonstrate this secondary minimum.

The profile of this section shows that in this season also there are four water layers with a similar arrangement to that found in September. The surface layer is, on the whole, much thicker here, as it extends down to 100 m. at some stations, and the average values of pH within this layer are higher. The lower limit of the phytoplanktonic layer has been pushed deeper by the thermocline and the density gradient is not yet steep enough to shut off the supply of nutrient salts.

Below the surface layer is the primary minimum pH layer which represents that water mass, which fails to pass through the Straits of Bab-el-Mandeb on account of the great volume of the Red Sea deep current and is turned back into the Gulf. It was also suggested (*vide supra*, p. 144) that the eastward-moving portion of this mass lay on the African side. In this profile the lowest pH values within this layer are found on the African side, which shows that oxidation on that side is in a more advanced stage on account of the age of that portion of the water layer.

The Red Sea deep current is represented by the secondary maximum pH layer, which is seen in the profile to have a greater thickness than it had in September. Finally, we have the secondary minimum pH layer, which we have assumed to represent a current from the open Arabian Sea creeping westwards along the bottom of the Gulf. This layer is now much thinner than it was in September and it seems, therefore, that its volume is subject to seasonal changes.

*Section D: Conditions in October* (Text-fig. 9).—Observations along Section D were made in October at three stations (32, 38 and 25).

The surface pH varies from 8.05 on the northern side of the Gulf to 8.09 on the southern side. Below the shallow depth of 10 m. the pH falls rapidly with increase of depth and then gradually until it reaches a primary minimum value of 7.76–7.71 at a depth of 50–100 m. Still deeper the pH rises again until it reaches a secondary maximum value of 7.86–7.92 near the bottom at Stations 25 and 32 and at a depth of 200 m. at Station 38. At the latter station the pH decreases again to a secondary minimum value of 7.75 at a depth of 400 m. and then increases to a tertiary maximum of 7.88 at a depth of 800 m., below which it diminishes to a tertiary minimum near the bottom (*vide* Text-fig. 2, Station 38).

The greatest vertical pH gradient along this section is well pronounced, amounting to 1.00–1.50 pH units, and occurs between the depths of 10–20 m. The simultaneous development of well-pronounced pH and temperature gradients at the same levels along this section is in common with all our observations in the Gulf in September.

The lapse of time between the observations at the different stations along this section, the position of the section itself at the mouth of the Gulf, where several water masses are bound to meet and mix, and the complicated topography of this eastern region combine to make it difficult to form a clear picture of the water layers in this profile. Moreover, the lack of observations in the long stretch between Stations 38 and 25 makes our presentation of the conditions across the central part of the Gulf only approximate.

Nevertheless, some of the general features common to other sections in the Gulf can be pointed out without difficulty. Below the surface layer, which is only about 10 m.

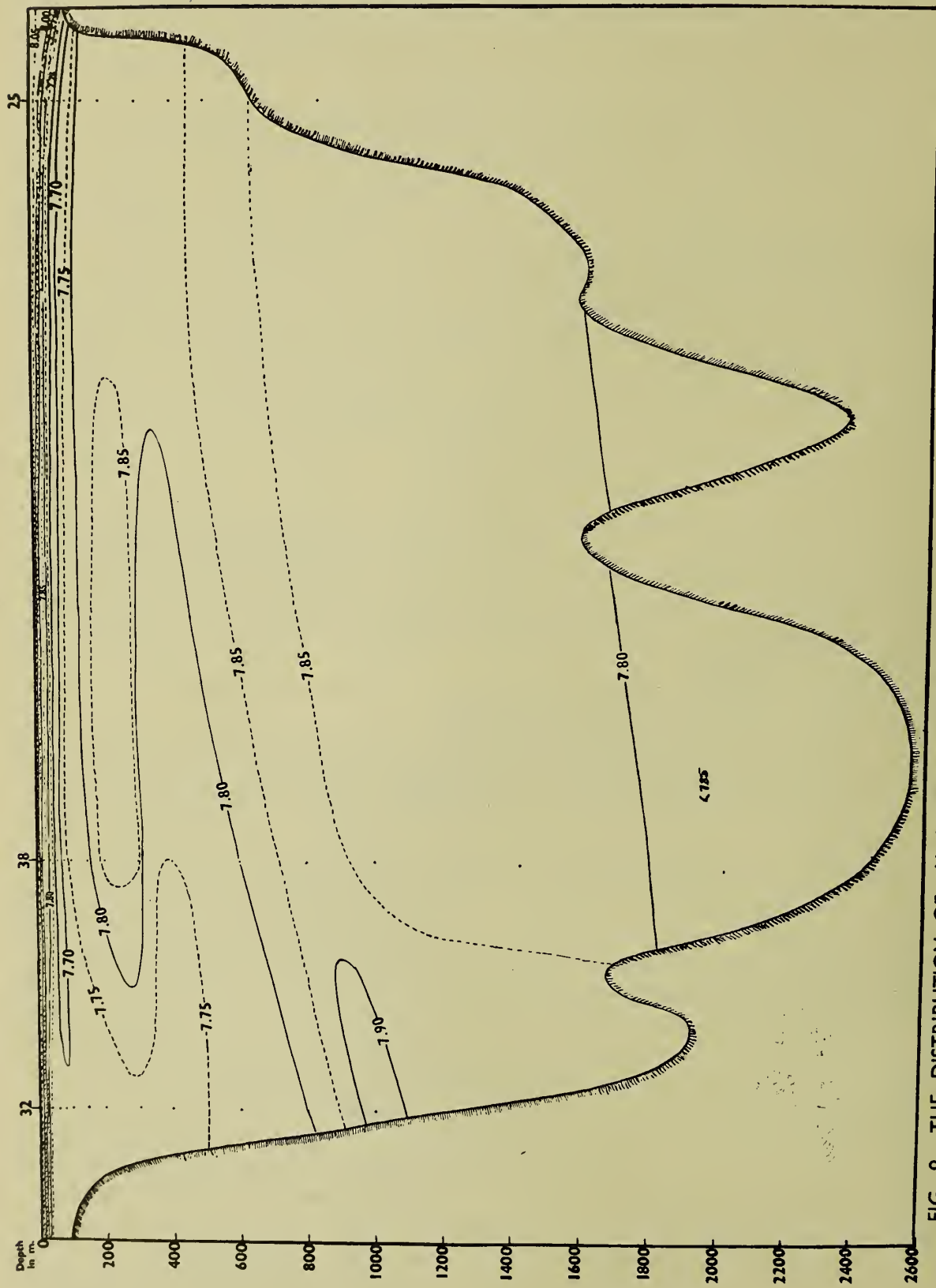


FIG. 9.—THE DISTRIBUTION OF pH ALONG SECTION D ACROSS THE EASTERN END OF THE GULF OF ADEN (OCTOBER).



thick, is the minimum pH layer which attains a considerable thickness on the northern side of the Gulf. Along the remainder of the section its thickness is, however, reduced owing to mixing with other water masses. As the outflowing Red Sea water reaches this part of the Gulf it becomes difficult to trace it clearly. We find, however, at a depth of 1000 m. at Station 32 a water mass, with a pH value of 7.91, which represents the Red Sea bottom current. At a depth of 200–300 m. in the position of Station 38 we find another mass with relatively high values of pH (7.85). The origin of this mass is not clear, but it probably represents an offshoot of the main Red Sea water mass. The deep parts of the Gulf are seen to be filled with water having pH values between 7.80–7.85.

*Section D: Conditions in May* (Text-fig. 10).—Observations of pH along Section D were repeated in May at two stations only (181 and 183).

The surface pH varies from 8.06 to 8.08; descending below the surface the pH changes slightly with depth until it reaches a minimum value of 7.69–7.70 at a depth of 200 m. With increasing depth the pH rises until it reaches a secondary maximum of 7.82–7.85 at a depth of 800–1000 m., below which it falls to a secondary minimum value of 7.70–7.75 in the vicinity of the bottom.

The arrangement of the water strata in the profile of this section is very similar to that of Section C (May) and calls for but little comment. It is seen that the surface layer is now much thicker than it was in October and possesses higher pH values. Below the surface layer is the primary minimum pH layer. The Red Sea deep current is represented by a water mass with pH values varying from 7.80–7.85. Finally we find the secondary minimum pH layer, which fills the deeper parts of the Gulf and represents what we assumed to be a current from the open Arabian Sea, creeping westwards along the bottom of the Gulf. The pH values within this deep water are now lower than they were in October and it seems, therefore, that the character of this water, as well as its volume, is subject to seasonal changes.

*Section E: Conditions in October* (Text-fig. 11).—Observations of pH in the Socotra Channel were made along Section E at two stations (23 and 30) in October. The pH of the surface waters is comparatively high and uniform in the upper 20–40 m. With increasing depth the pH decreases until it reaches a primary minimum value of 7.79–7.83 at a depth of 150 m., below which it increases again to a secondary maximum at a depth of 300 m. Below this the conditions are different north and south of the Socotra-Guardafui ridge. At Station 30 the pH-depth curve exhibits two weak minima, while at Station 23 it shows only one minimum.

Below the surface layer there is a large water mass with intermediate pH values varying from 7.85–7.95. This mass is split up into two parts by a weak minimum represented by an intrusive tongue of water at a depth of 150 m. in the position of Station 23, but the presence of a minimum pH layer in the usual sense, *i. e.* as defined by values less than 7.80 is practically non-existent. It is improbable that this weak minimum is due to an error of observation, but is rather a result of the unusual conditions in this region, where, owing to the peculiar position of the section, several water masses come presumably from various directions. At a depth of 600–800 m. on the northern side of the ridge there is another body of water with similar intermediate values of pH, and it is possible that this body of water is the continuation of the water above it, and that it has been split off by the secondary weak minimum found at a depth of 400 m. This body of water can hardly be described as representing the Red Sea bottom current, since the outflow of

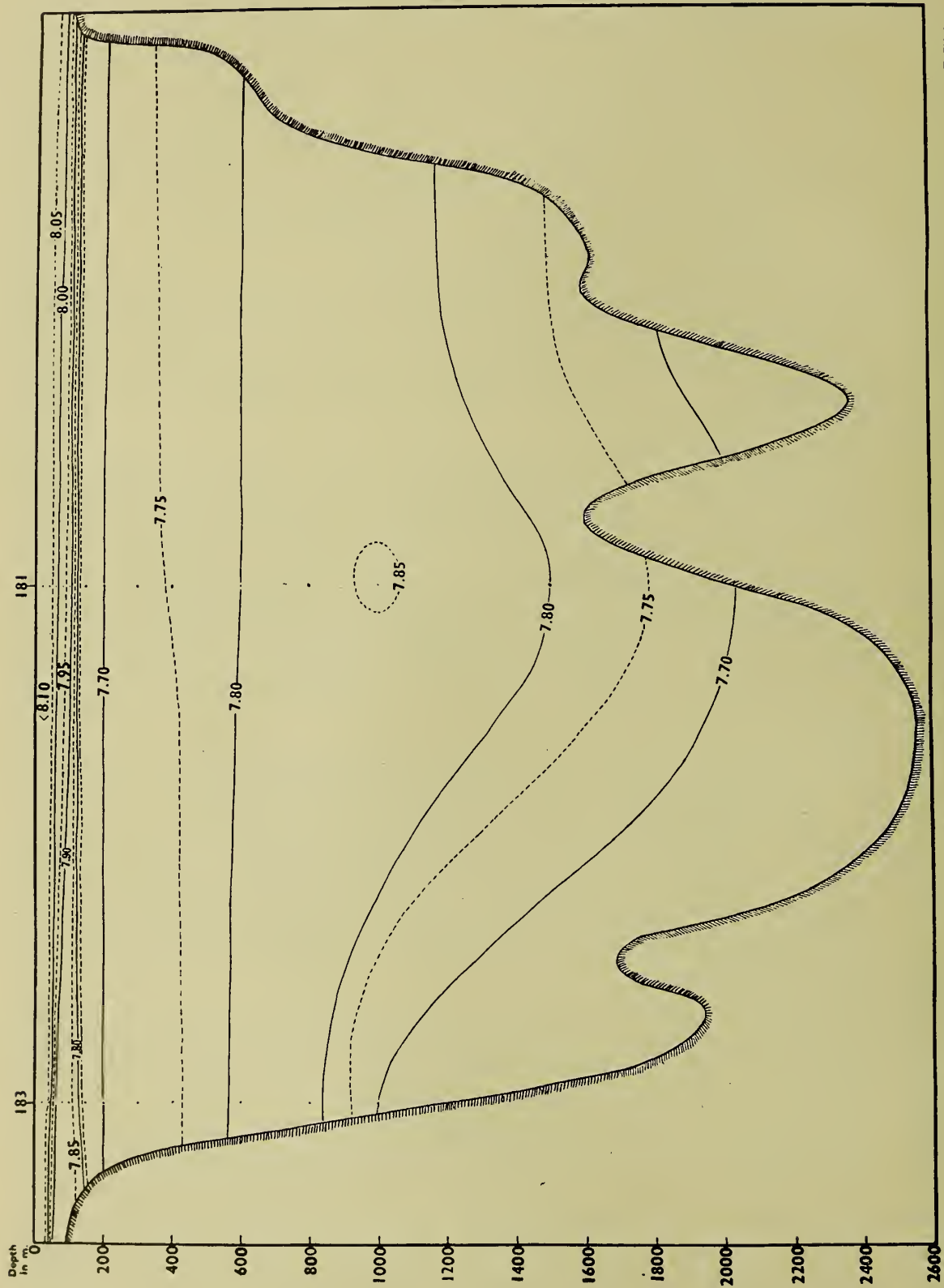


FIG. 10.—THE DISTRIBUTION OF pH ALONG SECTION D ACROSS THE EASTERN END OF THE GULF OF ADEN (MAY).

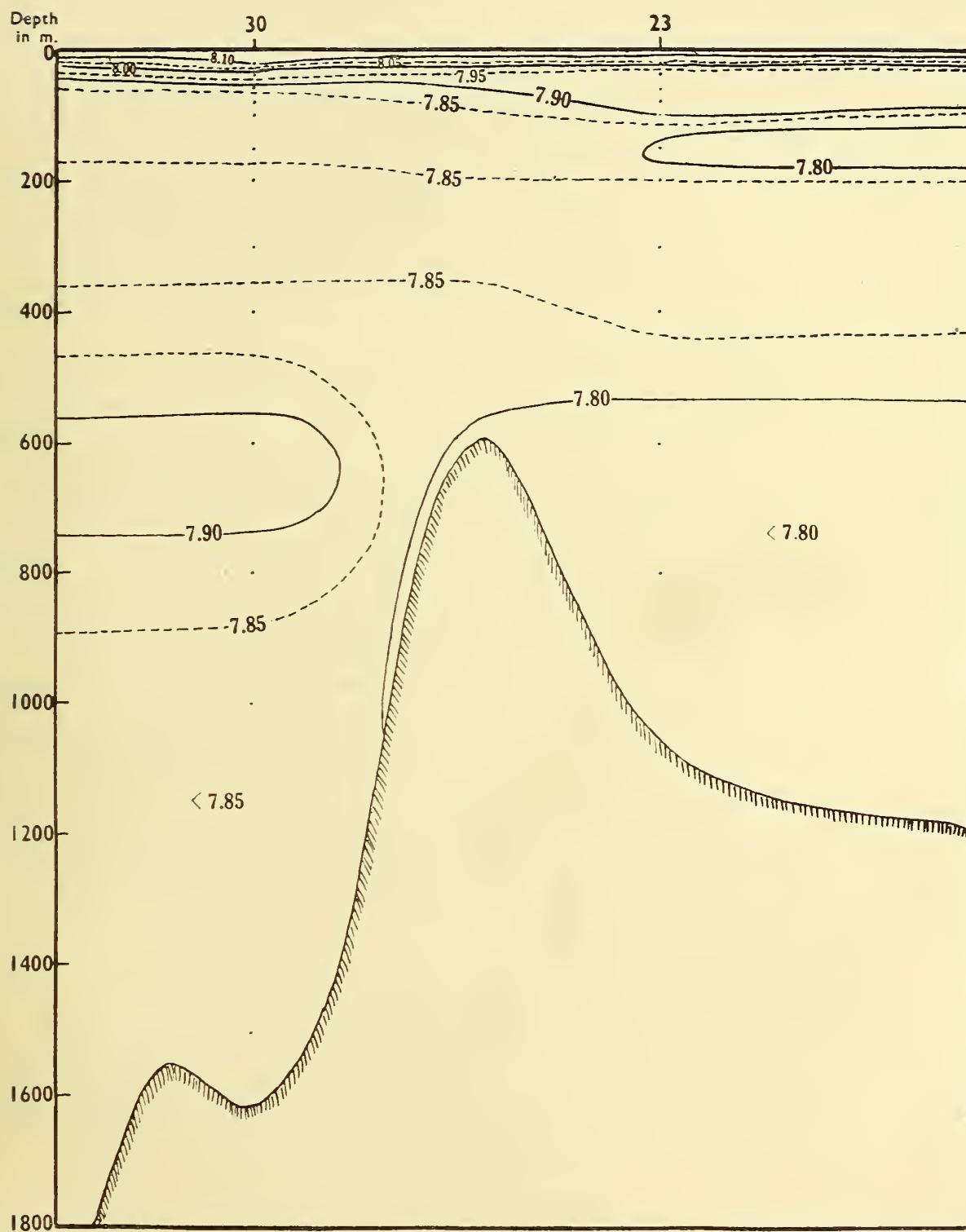


FIG. 11.—THE DISTRIBUTION OF pH ALONG SECTION E THROUGH SOCOTRA CHANNEL (OCTOBER).



this current is small in this season and has already been seen to be vanishing in the profile of Section D (October).

The deep water lying north of the ridge has pH values less than 7.85, and is seen to have originated south of the ridge. This water passes over the ridge into the Gulf of Aden and it is probable that the current which creeps westwards along the bottom in the Gulf of Aden is its continuation.

*Section E: Conditions in May* (Text-fig. 12).—On the return journey observations were repeated along Section E in May at the same two positions (Stations 174 and 175). We find again that conditions are different north and south of the Socotra-Guardafui ridge. South of the ridge (Station 174) we find that below the thick surface layer the pH falls somewhat abruptly until it reaches a minimum value (7.73–7.74) at a depth of 200–400 m., and then increases slightly near the bottom.

North of the ridge we find below the thinner surface layer a body of water having intermediate values of pH (7.88–7.99) with a nucleus about a depth of 200 m. As this body of water cannot be said to have originated in the Gulf of Aden, with the water strata of which we are now familiar, it is reasonable to assume that it has its origin in the open ocean. It is also clear that this water does not approach the position of Station 30 in the main over the ridge, but rather from a diagonal direction, which is possibly easterly to south-easterly. This water will be traced later to an important layer with similar character found in the open ocean and known as the Antarctic intermediate current.

Below this body of water the pH of the deeper water is low and uniform throughout the entire water column north of the ridge. This deeper water is also seen in this profile to have originated south of the ridge, and since it is similar in character to the current creeping along the bottom in the Gulf of Aden, the latter can be considered as its continuation. A similar conclusion regarding the origin of this bottom current in the Gulf during the last season has already been reached. It is not possible at this stage to trace the source of this water in the open ocean any further, especially since the number of observational stations on this section is very limited.

The deep Red Sea current cannot be detected in this profile, and it is possible that the position of this section does not coincide with the main direction of its flow. It is equally possible that by the time it leaves the Gulf of Aden its pH has fallen so low that it becomes difficult to trace.

#### THE GULF OF OMAN, THE ARABIAN SEA, AND THE NORTH-WESTERN INDIAN OCEAN.

In the Gulf of Oman, the Arabian Sea and the north-western Indian Ocean area pH observations were made along eight sections (F–M), two of which run off the South Arabian coast, one parallel to it, one in the Gulf of Oman, one off the African coast and three across the ocean between the Asiatic and African coasts.

##### *The Arabian Coast.*

Observations along sections F and G off the South Arabian coast and along Section H, which runs parallel to the coast, were made in October–November.

*Section F* (Text-fig. 13).—This section runs off the South Arabian coast in the vicinity of Kuria Muria Islands, and observations along it were taken at two stations, 41 and 43,

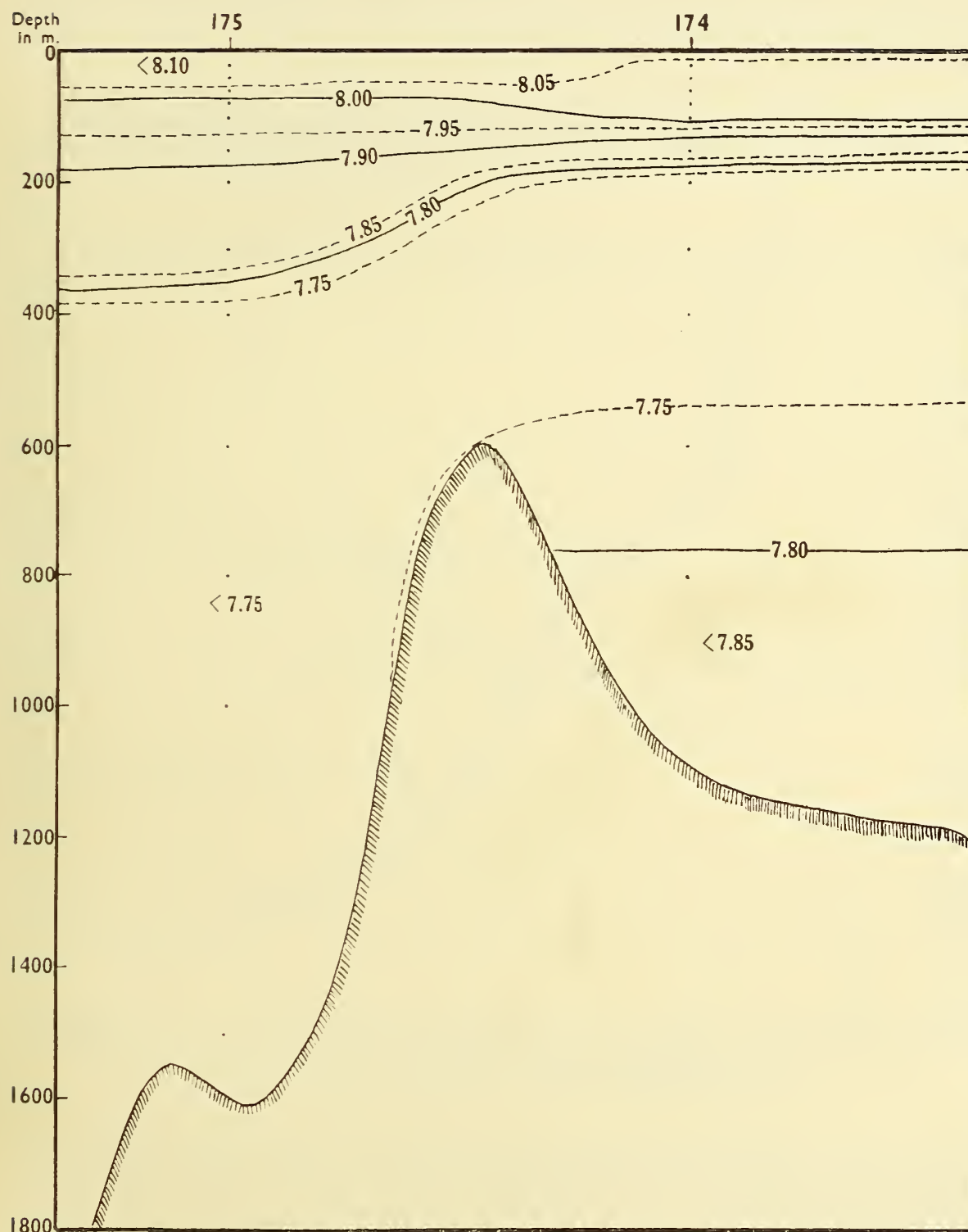


FIG. 12.—THE DISTRIBUTION OF pH ALONG SECTION E THROUGH SOCOTRA CHANNEL (MAY).

in October. The two main features in this profile are the concentration of pH isolines in the immediate neighbourhood of the surface and the massive thickness of the minimum pH layer as defined by pH values less than 7.80.

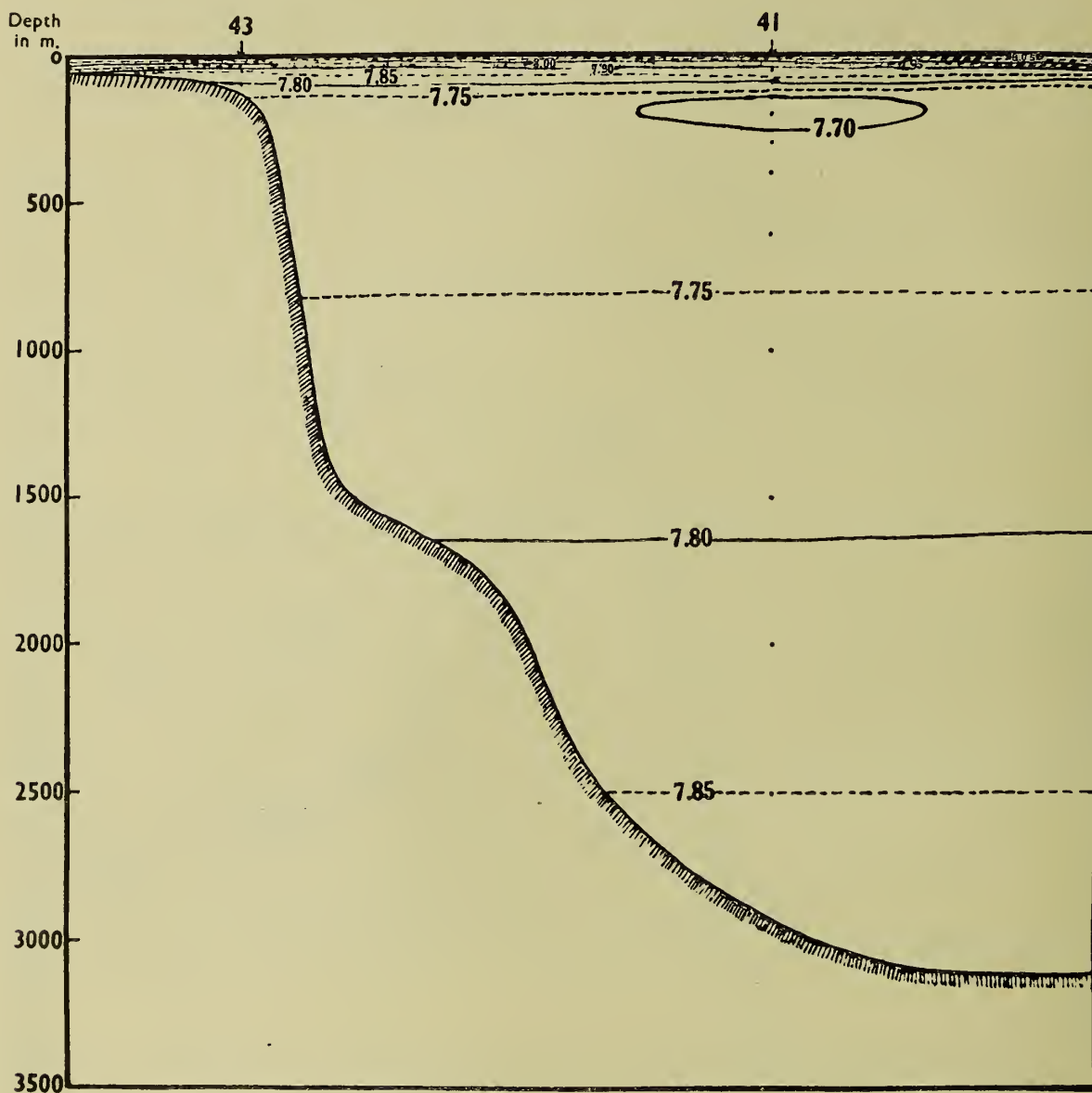


FIG. 13.—THE DISTRIBUTION OF pH ALONG SECTION F OFF THE ARABIAN COAST IN THE VICINITY OF KURIA MURIA ISLANDS.

The surface pH varies from 8.07 at the seaward station to 8.11 at the inshore station, indicating a higher phytoplanktonic activity in the inshore waters. The surface layer, which amounts in thickness only to 30–40 m., is separated from the layer below it by pronounced vertical gradients. It is noteworthy that along this section also these gradients occur at about the same depth as the principal thermocline.

Below the surface layer the pH falls abruptly and continues to fall with increasing depth until it reaches a minimum value of 7.68 at a depth of 150 m. The thickness of the minimum pH layer amounts to about 1000 m., thus revealing the presence of oxidation



processes on a vast scale. As we have already seen in the profiles of the Gulf of Aden sections, great thickness of the minimum pH layer and a position immediately below the surface layer seem always to be associated with the presence of a sharp thermal boundary below the surface layer. The minimum pH layer is therefore in the first place a result of the hydrographical and meteorological conditions in these coastal regions. As we shall see later, this low pH water formed in these coastal regions is the source of the so-called North Indian deep current, which moves southwards.

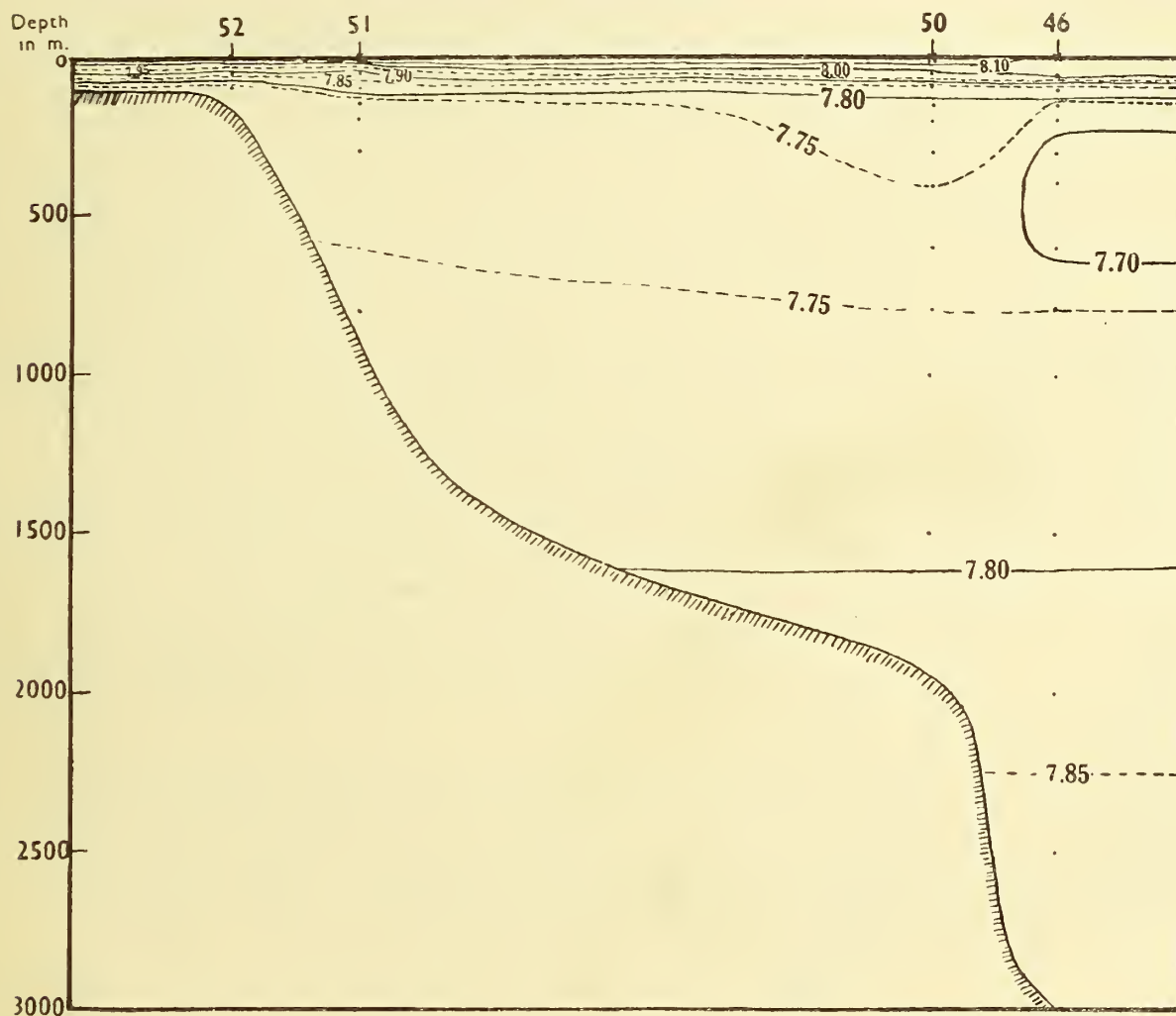


FIG. 14.—THE DISTRIBUTION OF pH ALONG SECTION G OFF RAS MADRAKA ON THE ARABIAN COAST.

At the deep seaward station the pH reverses its vertical gradient below the depth of minimum pH and continues to increase until it reaches values higher than 7.80 in the deep water. This deep water will be shown later to have its origin in the northward movement of the Antarctic intermediate current.

*Section G* (Text-fig. 14).—This section runs off the South Arabian coast in the vicinity of Ras Madraka and observations along it were made at four stations (46, 50, 51 and 52) in October–November.

The vertical distribution of pH along Section G is essentially the same as in the last section (*cf.* Text-figs. 13 and 14). The surface pH is again higher (8.13–8.14) at the

inshore stations than it is further to seaward, and is, on the whole, relatively high compared with the surface pH in other regions, reflecting a more intense phytoplanktonic activity.

The surface layer is separated from the layer below by distinct gradients, which occur at about the same depths as the principal thermocline.

The thickness of the minimum pH layer, which amounts to about 1470 m., is the most marked feature of pH distribution along this section. In the deep water underlying this minimum pH layer the pH is comparatively high. This deep water does not cover the continental slope to any great extent, and has obviously come from the south.

It is thus seen that we can distinguish at least three water strata off the South Arabian coast: a surface layer, the minimum pH layer which corresponds to the North Indian deep current, and the deep water, which comes from the south.

*Section H* (Text-fig. 15).—Observations of pH along Section H, which runs parallel to the South Arabian coast, were made at three stations (39, 40 and 82) in October–November.

The distribution at Station 82 is essentially similar to that along Sections F and G. Here we find a massive minimum pH layer below the surface layer and finally the deep water. At Station 39 we find, however, a less massive minimum pH layer separated from the surface layer by a large body of water with intermediate values of pH. At Station 40 this latter water constitutes the bulk of the water column. Large volumes of this water, characterized by intermediate pH values, are thus met with for the first time in our area. The minimum pH layer is practically non-existent here and its usual position in the water column has been occupied by this water with intermediate pH values. From our description of the horizontal distribution of pH it will be seen that this water owes its presence to the northward movement of the Antarctic intermediate current. It is further noticeable that the water between the surface layer and the minimum pH layer in the position of Station 39 is in continuation with the main column of this water, which is split up there into an upper and a lower part by the intrusion of the minimum pH layer. We may, therefore, speak of the upper Antarctic intermediate current and the lower Antarctic intermediate current.

Whereas the lower Antarctic intermediate current fills the great depths in this profile, the upper current sends a branch to the westward, here found below the surface layer at Station 39. This is probably the source of the water with intermediate pH values found in similar position north of Socotra–Guardafui ridge at Station 30. A less marked easterly branch of the upper Antarctic intermediate current is also noticeable.

### *Gulf of Oman.*

*Section I* (Text-fig. 16).—Observations of pH were made in November along Section I at four stations (76, 81, 61 and 83).

The main features of the profile of this section are essentially similar to those of the sections off the South Arabian coast, namely, the concentration of isolines near the surface and the great thickness of the minimum pH layer. The surface layer varies in thickness from 20 to 60 m. The greatest vertical pH gradients along this section occur strictly at the same depths as the principal thermocline. Below the surface layer the pH falls abruptly and then gradually with increasing depth until it reaches a minimum value of 7.62–7.72 at mid depths (600–1000 m.). At Station 76, the most northerly one, there is, however, an intrusive tongue of water with comparatively high values of pH, which gives

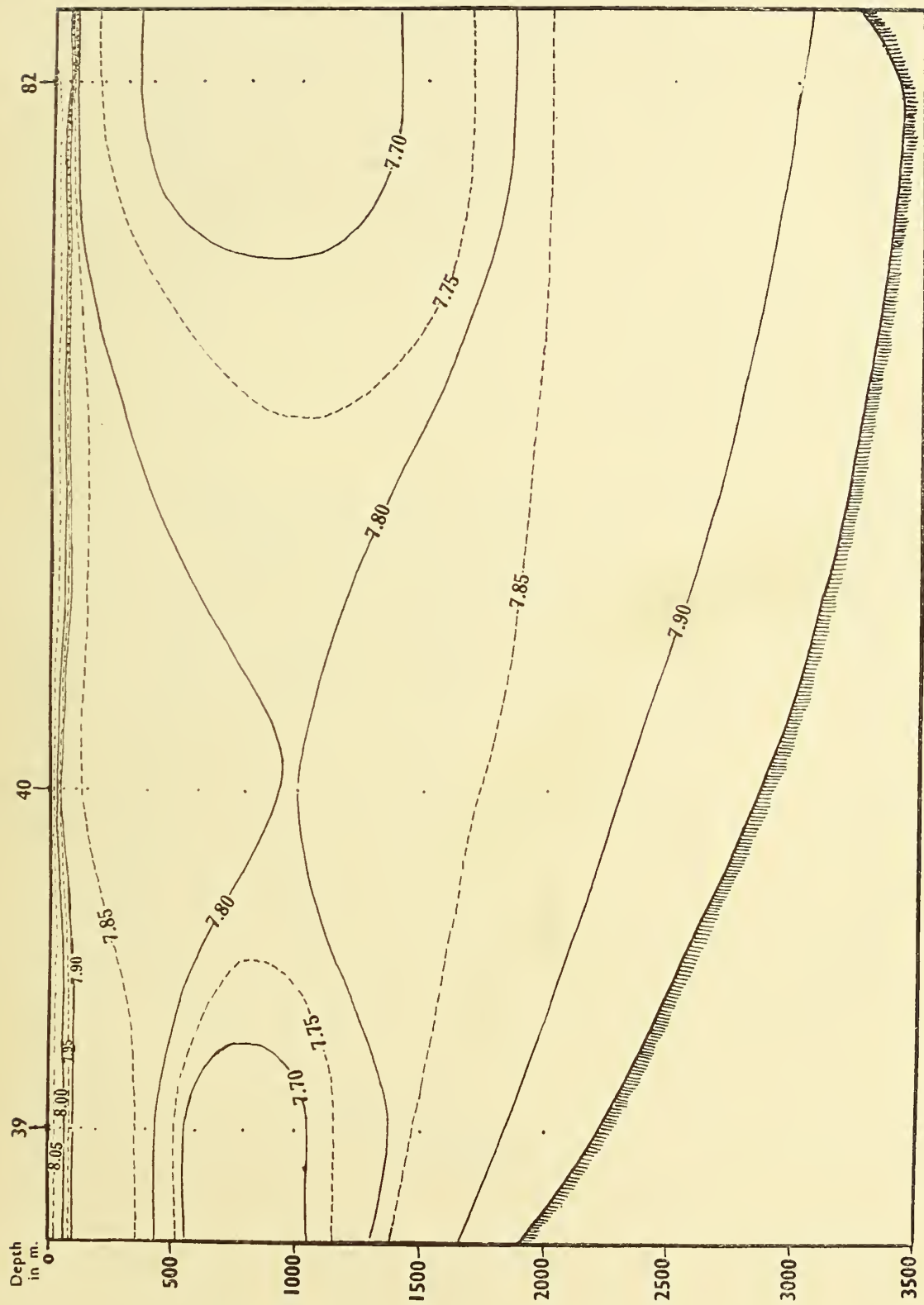


FIG. 15.—THE DISTRIBUTION OF pH ALONG SECTION H PARALLEL TO THE SOUTH ARABIAN COAST.



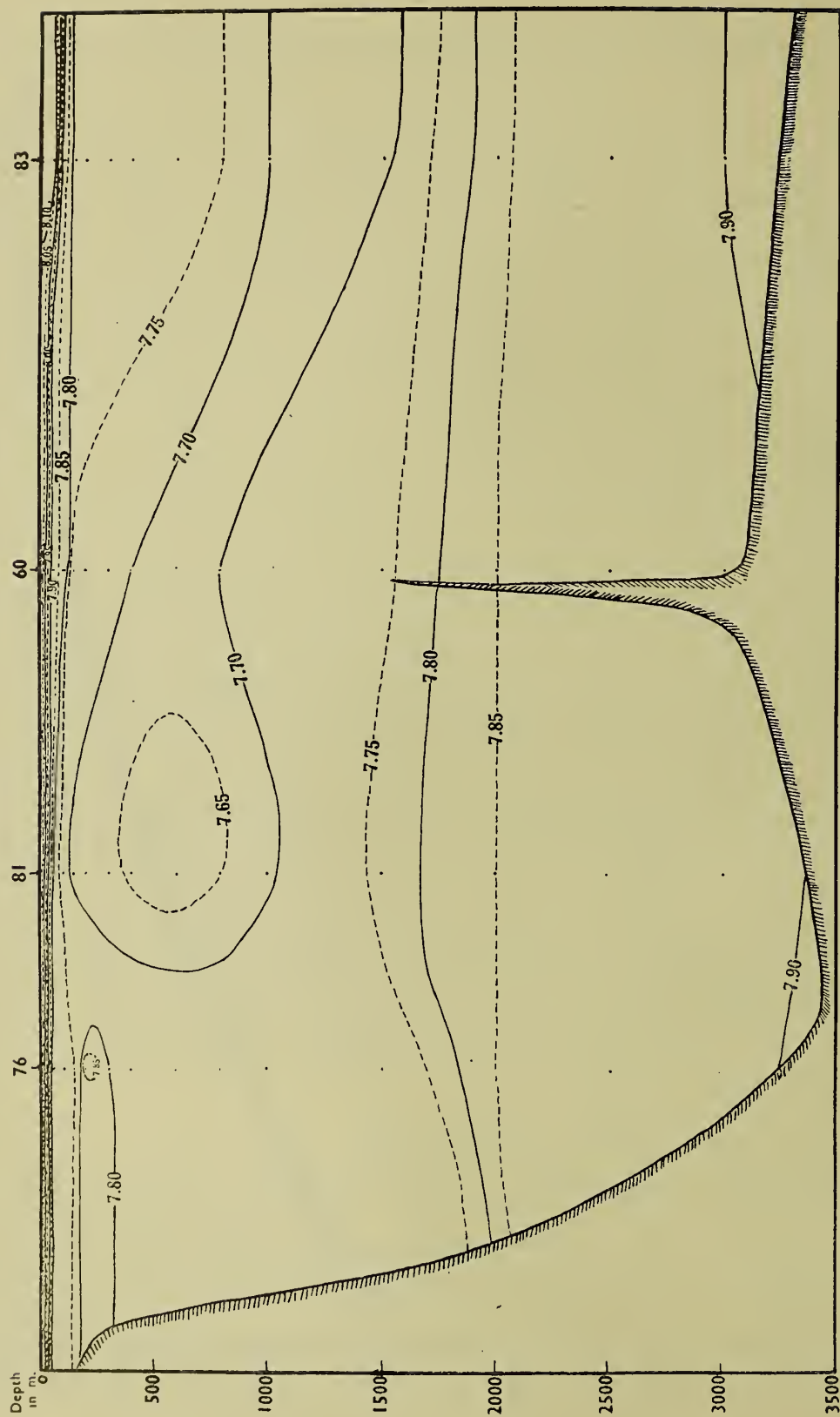


FIG. 16.—THE DISTRIBUTION OF pH ALONG SECTION I IN THE GULF OF OMAN.

rise to a secondary maximum at a depth of 200 m. Although we have not secured any observations from the Persian Gulf, it seems very probable that this intrusive tongue flows out from the Persian Gulf as this is the only obvious source.

The volume of the minimum pH layer is well marked in this profile and it is here that it attains a very great thickness (1670–1750 m.). It is also in this profile that the upper boundary of the minimum pH layer (upper 7·80 isoline) shows a closer approach to the surface than in any other section in the Arabian Sea or the north-western Indian Ocean. Its lower boundary (lower 7·80 isoline) lies deeper here than it is in any other section. If the assumption put forward above, that the boundaries of the minimum pH layer represent the limits to which organic oxidations in the sea are confined, is correct, the minimum pH layer in this profile must be the seat of far-reaching oxidation processes. The order of magnitude of the lowest pH values within this layer suggests that a relatively more intense oxidation is taking place here than anywhere else in the Arabian Sea or the north-western Indian Ocean. It is interesting to note in this connection that the lowest pH values within this layer are found at Station 81, which lies off Ras el Hadd, a locality remarkable for the presence of hydrogen sulphide in the bottom deposits obtained from its vicinity.

When we examine the temperature observations along this section we find that there is a well-pronounced temperature gradient (and consequently a density gradient) near the surface. We have already assumed that the presence of such a sharp boundary between the surface and the minimum pH layer makes the latter dependant for its oxygen supply on lateral exchanges which leave it in a state of relative stagnation. This low pH water formed here and off the South Arabian coast moves, as we shall prove later from our description of horizontal distribution, southwards as the North Indian deep current. The way in which the pH isolines within this layer slope down as they run to the south suggests that this water sinks on its way southwards.

Below the surface layer and above the upper boundary of the minimum pH layer there is, at the most southern station on the section, a band of water with pH values of *ca.* 7·85. The origin of this water is the easterly component of the upper Antarctic intermediate current described under Section H.

In the deeper water below the lower boundary of the minimum pH layer the pH becomes higher again (7·85–7·90). This water, as well as the deep water found in sections off the South Arabian coast, will be proved, when describing the horizontal distribution of pH, to have its origin in the northward movement of the Antarctic intermediate water.

To sum up, the chief features of the vertical distribution of pH along Section I are : (1) The concentration of the isolines near the surface ; (2) the massive thickness of the minimum pH layer ; (3) the low magnitude of the minimum pH values ; (4) the existence of the Persian Gulf water at the northern station as an intrusive tongue within the minimum pH layer (5) the existence at the southern station of a band of water with intermediate pH values between the surface layer and the minimum pH layer; and (6) the relatively high pH values of the deep waters.

#### *Sections between India and Africa.*

*Section J* (Text-fig. 17).—During December pH observations were made between Bombay and Mombasa at seven stations (91, 92, 93, 95, 97, 101 and 102) along Section J, which runs in a north-east to south-west direction.

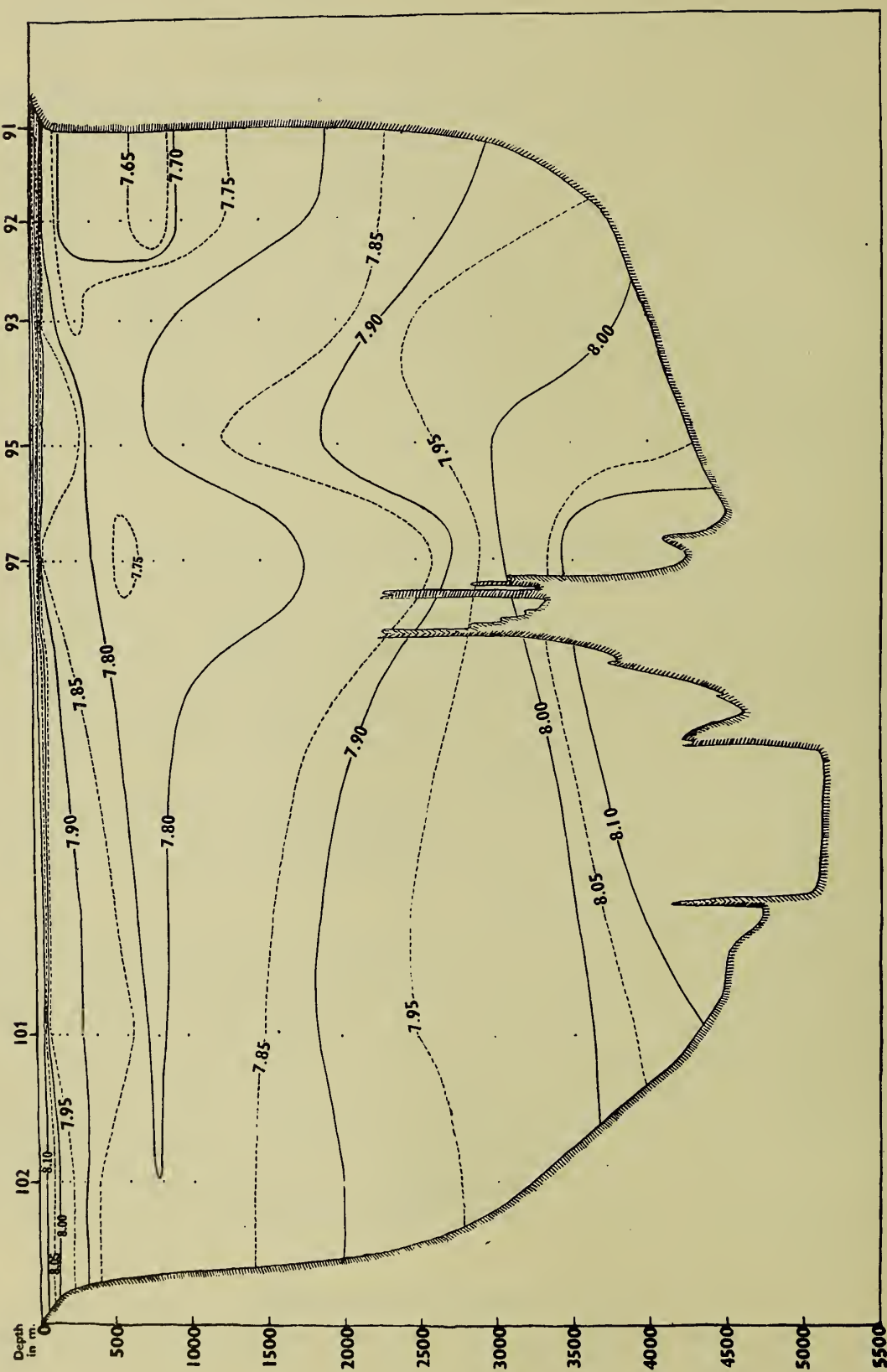


FIG. 17.—THE DISTRIBUTION OF pH ALONG SECTION J FROM POINT MALINDI TO BOMBAY.



The average surface pH is on the whole higher along this section than it is along the other two sections (L and M) which run across the ocean between the Indian and African coasts. The surface pH decreases from east to west, the change following the trend of surface temperature. The thickness of the surface layer decreases in the opposite direction, *i. e.* from west to east. Within the surface layer the isolines are concentrated on the extreme right of the profile off the Indian coast, but are widely spaced on the left-hand side near the African coast. The concentration of the isolines off the Indian coast is a feature in common with the distribution of pH along the sections off the South Arabian coast and in the Gulf of Oman, whereas the widely-spaced isolines near the African coast is similar to what we shall see later in the profile of Section K off the African coast.

Except at the extreme right of the profile there lies below the surface layer and above the minimum pH layer a body of water with pH values (7.85–7.95) which are intermediate between the high values of the surface layer and the low values of the minimum pH layer. This body of water reaches its greatest thickness in the south-western side of the profile, but its thickness diminishes as it passes north-eastwards until it is entirely absent off the Indian coast. Indications of this water were already shown to exist at Stations 39 and 40 on Section H, and we have assumed that this body of water with intermediate values of pH corresponds with the Antarctic intermediate current. Near the African coast it is seen to be continuous with the deep water below it; a similar continuity was already revealed when describing conditions at Station 40. Further north-eastwards the southward flow of the North Indian deep current splits it up into an upper and a lower portion, and we have ventured to speak of these portions as the upper Antarctic intermediate current and the lower Antarctic intermediate current.

The position and thickness of the minimum pH layer varies in this profile from one region to another. It is well-developed off the Indian coast and in the position of Station 97, but is almost non-existent off the African coast. This is a remarkable difference of pH conditions off the two coasts which must have far-reaching effects on the biological conditions. It is in this profile that the minimum pH layer attains its maximum thickness in the whole area of investigation, as it amounts to 1770 m. The upper boundary of this layer (upper 7.80 isoline) lies deepest on the African side of the profile, but rises gradually to only 80 m. below the surface near the Indian coast; its lower boundary (lower 7.80 isoline) is variable in position and lies between 800 and 1875 m. Owing to the upward movement of the lower Antarctic intermediate current in the position of Station 95 the minimum pH layer shows a tendency for division into two branches. The lowest pH values within this layer are found on the Indian side of the profile.

The water beneath the minimum pH layer has again pH values (7.85–7.95) intermediate between those of the low values of the minimum pH layer and the relatively high values of the bottom water, and as it is similar in character to that body of water between the surface layer and the minimum pH layer we feel justified in designating it as the lower Antarctic intermediate current. This water extends as deep as 3000 m. and has a nucleus at about 2000 m. in the south-western basin. The isolines within this water exhibit a prominent hump in the north-eastern basin and a less pronounced one in the south-western basin, a feature which indicates that this deep water wells up as it advances north. Had the line of stations at which pH observations were made been without a gap the actual course of the second hump might have been better defined.

In the deeper water below 3500 m. the pH is relatively high ( $>8.00$ ) and reaches a value of 8.14 in the vicinity of the bottom in the north-eastern basin and of 8.08 in the south-western basin. As will be shown later, this bottom water comes from the south and presumably is the Antarctic bottom current. But the exceptionally high pH values of this water near the bottom are puzzling, as one would expect water coming from the Antarctic to possess a lower pH on account of its high carbon dioxide content. We should, however, bear in mind the interaction between this water and the floor of the ocean under great pressure. Having a high carbon dioxide content this water would possess a strong solvent action. By its action on the floor of the ocean under great pressure this water

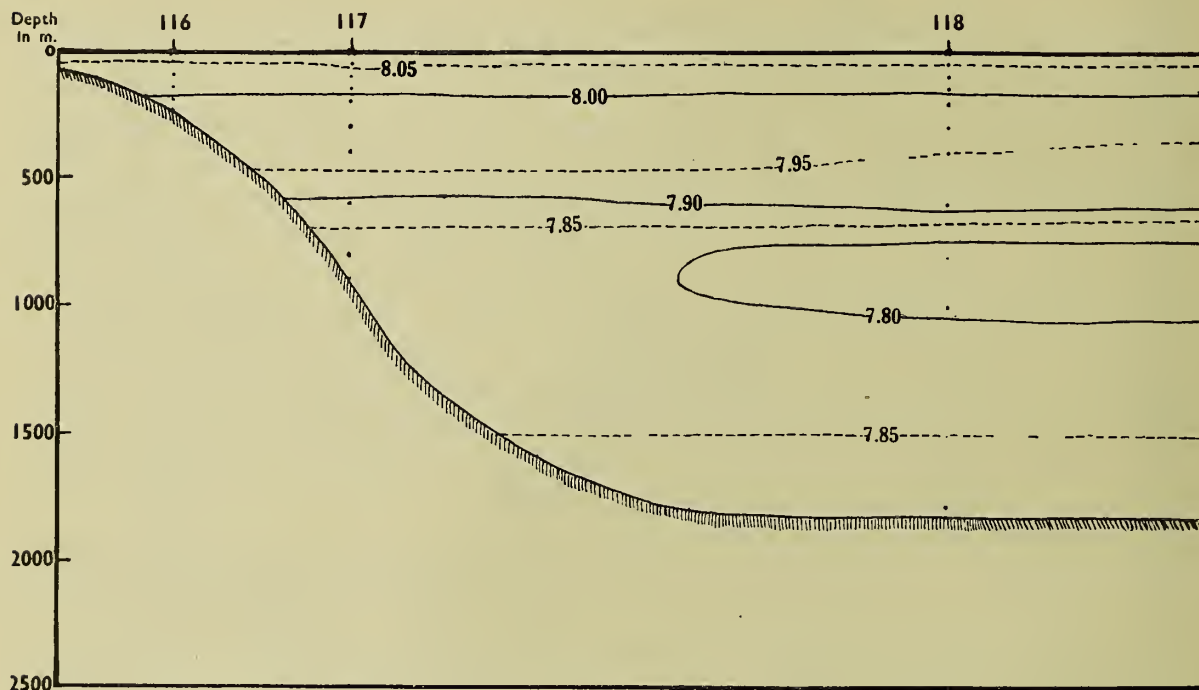


FIG. 18.—THE DISTRIBUTION OF pH ALONG SECTION K OFF THE AFRICAN COAST IN THE VICINITY OF MOMBASA.

reacts on the carbonate constituents of the floor and thus acquires a higher pH. The samples of red clay, known to be of low carbonate content, obtained by the present Expedition at Stations 166 and 167 (Sewell, 1935) in the north-eastern basin, support this suggestion and probably account for the somewhat high pH values of the Antarctic bottom current in this profile.

*Section K (off the African coast)* (Text-fig. 18).—In January pH observations were made at three stations (116, 117 and 118) along Section K, which runs off the eastern African coast in the vicinity of Mombasa. The vertical distribution of pH along this section presents certain marked contrasts to that along the Arabian coast and the Gulf of Oman sections.

The surface layer, the seat of phytoplanktonic activity, is characterized by its great thickness (150 m.) and its high average value of pH, thus indicating a higher phytoplanktonic activity both in magnitude and intensity. The absence of closely-spaced isolines from the surface layer, a feature which was well marked in the sections off the

Arabian coast and in the Gulf of Oman, is very conspicuous. The same feature was already noticed on the African side of Section J.

The minimum pH layer, as defined by values less than 7.80, is much reduced in this profile and appears as a sandwiched band of water only at the seaward station, but is entirely absent at the inner stations. This presents a further marked contrast to conditions off the Arabian coast, in the Gulf of Oman and off the Indian coast, where the minimum pH layer is massive and covers the great depths of the continental slope and shelf.

Between the surface layer and the minimum pH layer there is a massive layer of water with pH values ranging from 7.89–7.99. Near the African coast this layer is seen to be in continuity with the deep water, a feature which had already manifested itself

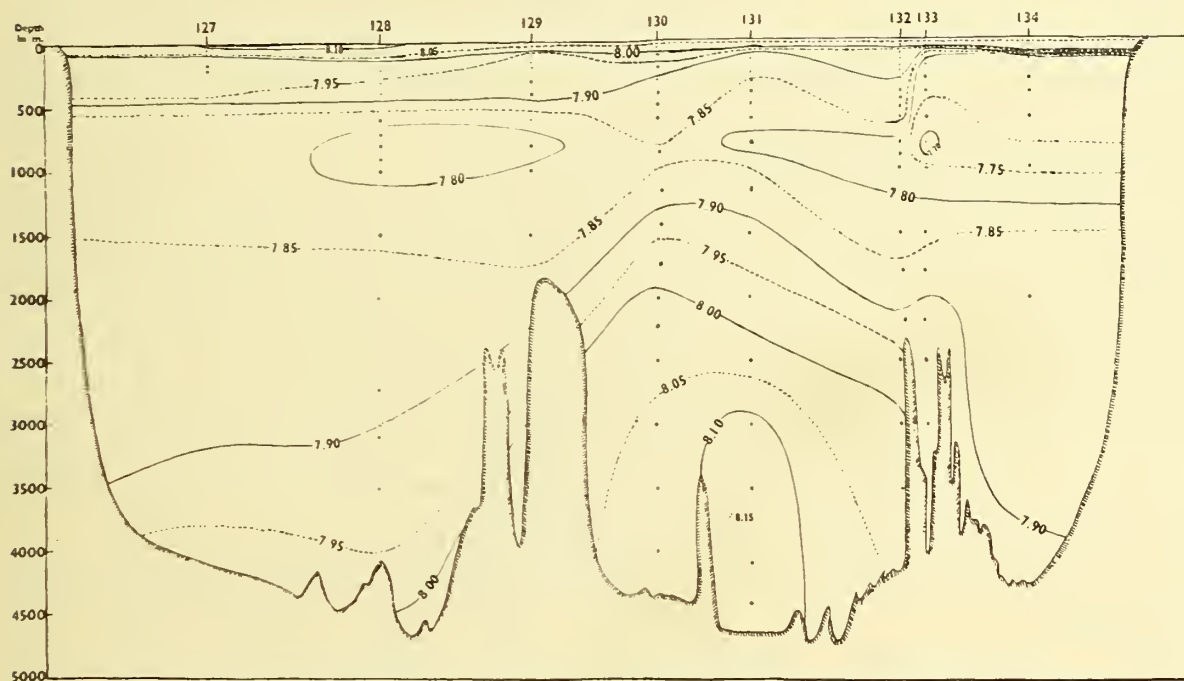


FIG. 19.—THE DISTRIBUTION OF pH ALONG SECTION L FROM ZANZIBAR TO KARDIVA CHANNEL.

off the African coast in Section J. We have already pointed out that this water, with intermediate values of pH, corresponds with the Antarctic intermediate current, but the continuation of this water in the vicinity of the African coast and its splitting into an upper and a lower portion by the intrusion of the North Indian deep current further east justifies our designation of these portions as the upper and lower Antarctic intermediate currents.

The great depths in this profile are filled with water of a comparatively high pH (7.84–7.89) which could, therefore, be described as the lower Antarctic intermediate current.

It is thus seen that we can distinguish from a pH standpoint four water masses in the profile of this section: the surface layer, the upper Antarctic intermediate current, a weak branch of the North Indian deep current and the lower Antarctic intermediate current.

*Section L* (Text-fig. 19).—Between Zanzibar and Kardiva Channel pH observations were obtained at eight stations (127–134) along Section L during the month of February.



The surface pH decreases from 8.05–8.11 at the surface to a minimum of 7.70–7.85 at a depth of 800–1000 m. The decrease in pH from high values at the surface to lower values downwards is more abrupt at the stations lying on the Indian side of the profile than at the stations lying westwards. The increase in pH below the depth of the minimum value continues with increase of depth to the greatest depth sampled at all stations on this section except at the stations lying between the Seychelles ridge and the Carlsberg ridge (Stations 130 and 131), where the pH decreases again slightly near the bottom.

Except at stations east of the Carlsberg ridge there is a mass of water with intermediate values of pH below the surface layer. Between the African coast and the Seychelles this mass of water has a pH of 7.92–7.99 and extends from a depth of 100 m. to about a depth of 450 m. East of the Seychelles the pH range of this water is lower; in the position of Station 130 this water extends as deep as 800 m., and in fact seems to be continuous with the deeper water below it. We have already come across a body of water, similar to this in character and similarly situated below the surface layer, which we described as the upper Antarctic intermediate current.

Beneath this water lies the minimum pH layer. The outstanding features of this layer are its great thickness east of the Carlsberg ridge and its absence from the position of Station 130, which gives it a characteristic twofold branching. The thickness of the eastern branch extends from 200 to 1200 m., but that of the western branch is variable and is, on the whole, much smaller. Unfortunately, no hydrographic observations were obtained from depths between 600 m. and 4000 m. at Station 127, but we can safely presume that the minimum pH layer is either much reduced in thickness or is non-existent.

The deeper water underlying the minimum pH layer possesses intermediate values of pH and it seems to well up between the Seychelles and Carlsberg ridges. We have described this water as the lower Antarctic intermediate current.

In the still deeper water the pH gets higher, and although the transition is not sharp these higher values are indicative of another kind of water, namely, the Antarctic bottom current.

*Section M* (Text-fig. 20).—During April pH observations were obtained between Kardiva Channel and Ras Hafun on the African coast at six stations (166, 167, 169, 170, 171 and 173) along Section M.

The general features of distribution along this section are essentially the same as along Sections J and L. Below the surface layer we find a stratum of water with intermediate pH values—the upper Antarctic intermediate current. This stratum is much reduced in volume in the positions of Stations 166 and 170. Beneath this stratum is the minimum pH layer—the North Indian deep current—which exhibits a threefold division. Below this layer lies one with intermediate values of pH—the lower Antarctic intermediate current. In the position of Station 167 the isolines within this water show a prominent hump, which is indicative of upwelling. Finally, we find in the great depths in this profile water with relatively higher pH—the Antarctic bottom current.

#### HORIZONTAL DISTRIBUTION.

The difference in hydrographical conditions in some regions of our area of investigation during the two monsoon seasons is too great to admit of combining together the observations made in the different seasons. In order, therefore, to avoid the possibility of

misrepresenting the horizontal distribution, we shall confine ourselves, in presenting this distribution, to a consideration of the observations obtained during the months of November–April, which cover well the period of the north-east monsoon in the Arabian Sea and the north-western Indian Ocean. By this arrangement the horizontal distribution of pH over the southern end of the Red Sea and the western end of the Gulf of Aden will be excluded, since observations in these regions were obtained either during September

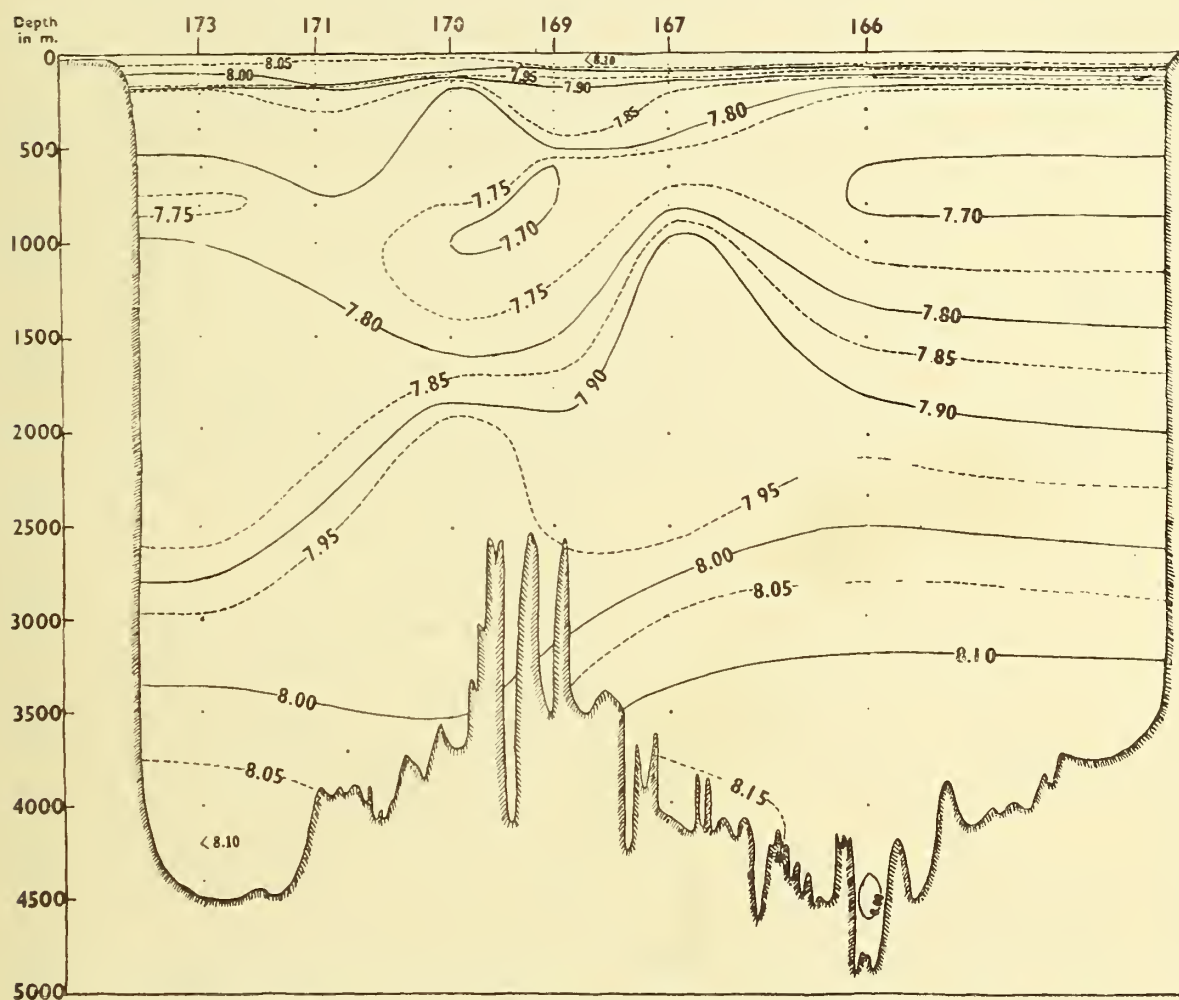


FIG. 20.—THE DISTRIBUTION OF pH ALONG SECTION M FROM KARDIVA CHANNEL TO RAS HAFUN.

or May. Conditions in these regions have been sufficiently elucidated by the description of vertical distribution.

By combining the pH observations obtained during the months of November–April we have constructed charts which show the horizontal distribution of pH at different levels. The isolines are drawn with intervals of 0.05 unit of pH.

#### *Surface.*

In any oceanic region the contact of the surface waters with the atmosphere tends to make the surface pH uniform, but the biological activity of the plankton, which proceeds with different intensities at different times, causes irregular variations. The regional

variations of pH at the surface thus become indistinct and the horizontal distribution of pH at the surface, and in fact in the upper 80 metres, does not lend itself to a comprehensive picture of the general conditions. For this reason no charts showing the distribution of pH at the surface or at levels between the surface and 100 m. depth have been given.

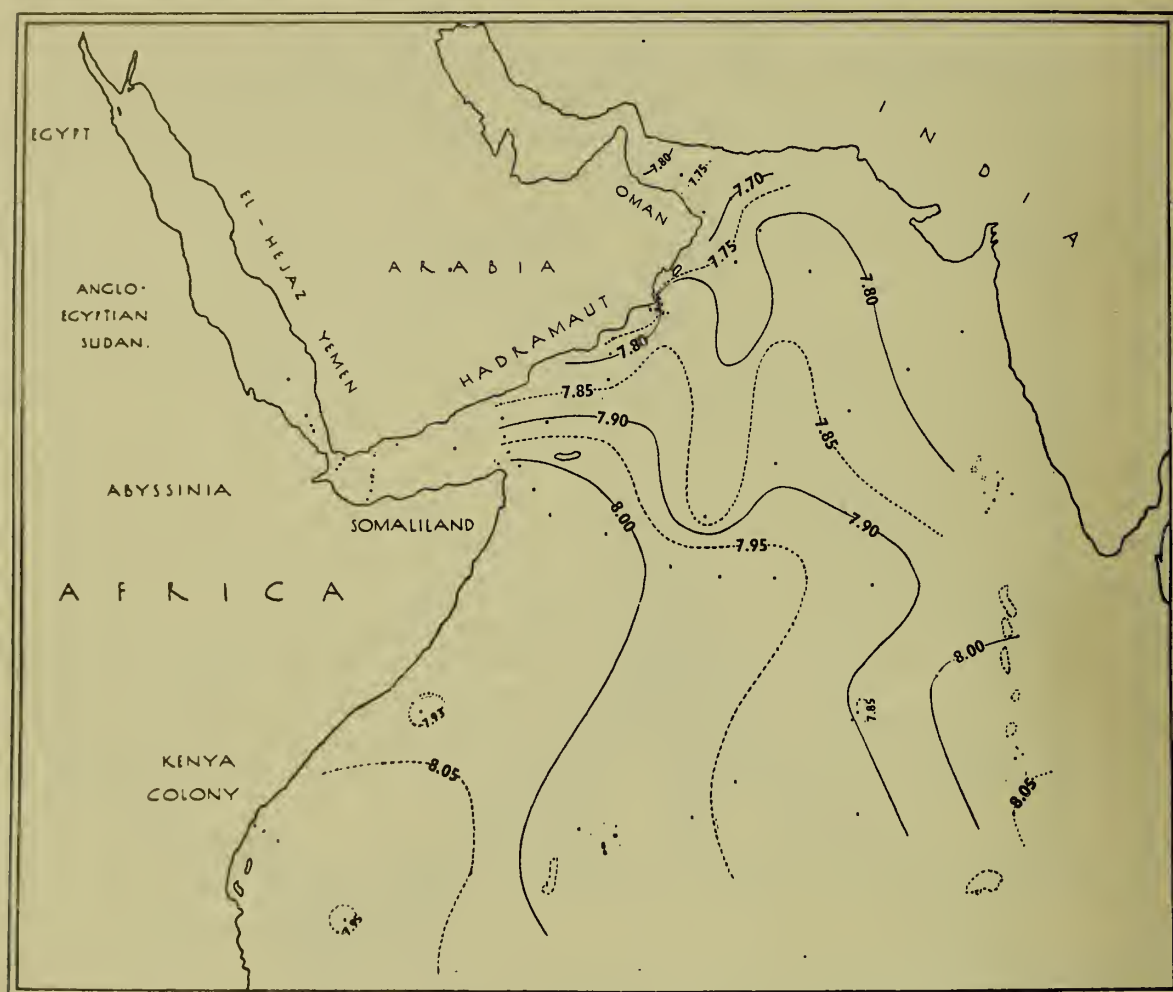


FIG. 21.—HORIZONTAL DISTRIBUTION OF pH AT 100 M.

The surface pH in the area under consideration varies from 8.04 to 8.16. This variation is due chiefly to irregularities in biological activity. The highest surface pH values (8.13–8.16) are found off the South Arabian coast (Stations 51, 52 and 53), off the coast of India (Station 91), and off the African coast (Station 101); these high pH values signify an increase of phytoplanktonic activity in these coastal regions. Similar high values occurred in the Central Arabian Sea (Stations 92 and 93).

*At 100 m. Depth (Text-fig. 21).*

Below the surface irregular variations due to biological activity become less and regional variations become more pronounced; hence the picture of pH distribution at



100 m. depth does not fail to display the regional variations occurring at this depth in spite of certain irregularities produced by the biological activity of organisms.

Low values of pH are found, as shown by the course of the 7.70 and 7.75 isolines, along the southern coast of Arabia. On the other hand, the highest values are found off the African coast and in the region of the Maldives. In the greater part of the area the pH increases in a south-westerly direction and in the Gulf of Oman as we pass up the Gulf.

The chart gives one the impression that water with low pH values originates in the coastal regions of South Arabia and tends to move in a southerly direction, whereas the water with high pH off the African coast, originating obviously further to the south, moves partly in a north-easterly direction and partly in a north to north-easterly direction. As this water meets the south coast of Socotra it is divided and passes partly between Cape Guardafui and Socotra Island and partly east of the island, where it seems to have a component directed towards the south coast of Arabia. The water with high pH in the region of the Maldives is seen to be moving westwards.

When conditions at this level are compared with those at the surface it is revealed that whereas at this level distinctly low values of pH occur off the South Arabian coast, distinctly high values occur at the surface. The cause of this abrupt change from high to low values off this coast finds its explanation in the presence of a well-pronounced thermocline along this coast, and it is possible that the high activity of phytoplankton at or near the surface is connected with increased death and decay at a lower level.

*At 200 m. Depth (Text-fig. 22).*

The general features of pH distribution at this level are similar to those at 100 m. ; low pH values occur, as shown by the course of the 7.70 isoline, along the south coast of Arabia and also along the coast of India, whereas high values are found mainly in the south. The pH increases in a southerly direction in the whole area. Passing up into the Gulf of Oman the pH also increases ; we have already attributed this increase to an out-flowing current from the Persian Gulf.

The expanse of the 7.70 isoline indicates that a greater area is occupied by water of low pH at this level than at 100 m. depth. The chart not only gives the impression that this water originates along the coasts of South Arabia and India, but also indicates that it flows away from its source of origin in southerly and south-westerly directions. This movement is shown by the more southerly positions which the 7.75 and 7.80 isolines now occupy. As the so-called North Indian deep current (see p. 185) is assumed to be formed in the coastal regions of the Arabian Sea and to have a southerly movement, it is justifiable to describe this low pH water itself as the North Indian deep current. As is seen from the chart this current shows a characteristic division into three bands, of which the eastern one, originating along the coast of India, moves in a south-westerly direction, the central band, originating off the South Arabian coast and in the vicinity of Ras el Hadd, moves southwards and the western band takes a south-westerly direction.

The water with high pH, which has apparently originated in the south, shows a corresponding division into three bands.

At the eastern end of the Gulf of Aden to the north of Socotra Island the horizontal gradient is very steep, the pH isolines showing a rapid transition from low to high values owing to the meeting of different water masses.

*At 300 m. Depth (Text-fig. 23).*

At this level the trend and arrangement of pH isolines are similar to those at 200 m. depth. The low pH water is found again along the coasts of South Arabia and India, and the high pH water in the southern region of the area. The pH increases in a south-westerly direction in the open ocean, but increases in a northerly direction in the Gulf of Oman. The more south-westerly position of the 7.85 isoline indicates a stronger influence of the low pH water with increasing depth.

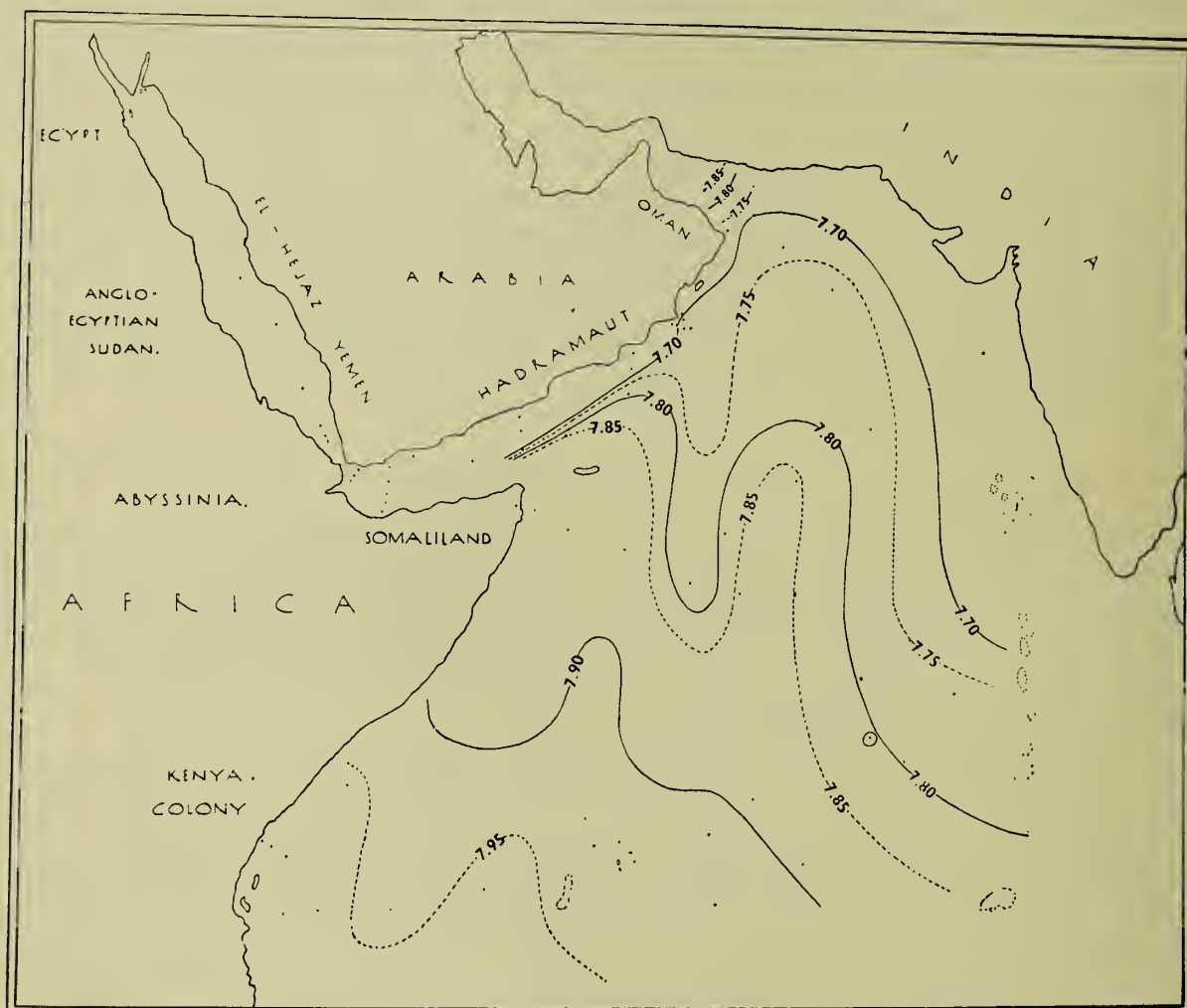


FIG. 22.—HORIZONTAL DISTRIBUTION OF pH AT 200 M.

*At 400 m. Depth (Text-fig. 24).*

The general features of distribution at this level are essentially similar to those at 300 m. The appearance of the 7.65 isoline at this level for the first time gives the picture a new feature. The movement of water with low pH southwards and south-westwards asserts itself more at this level, and on account of this movement the high pH water is confined to the south-western region of the area.

*At 600 m. Depth (Text-fig. 25).*

The most noticeable feature of distribution at this level is the marked predominance of low pH water in the area under consideration. The more southerly position which the 7.80 isoline now occupies indicates that with increase of distance from its principal sources of origin the water with low pH values sinks deeper and disperses into larger areas to the south.

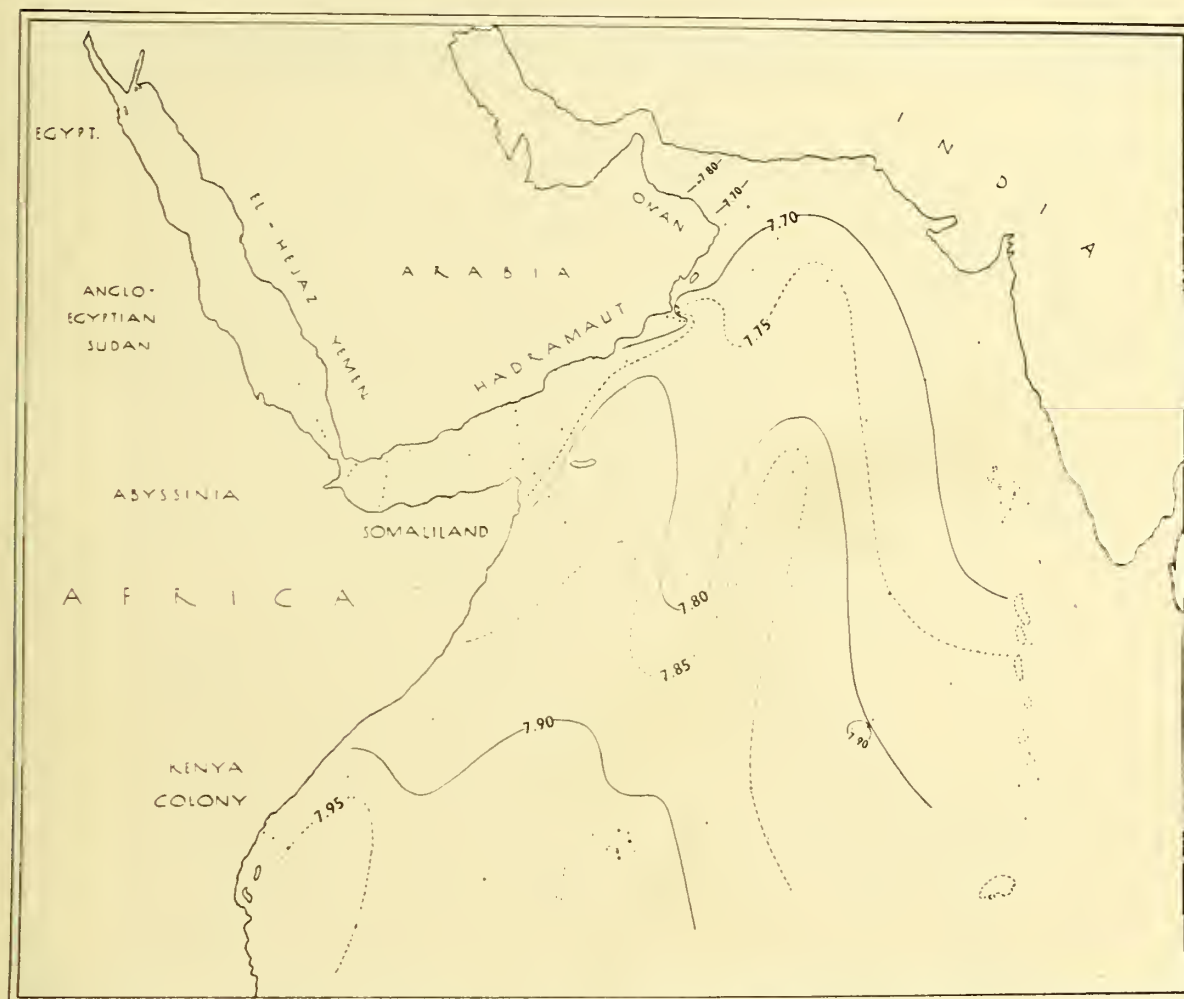


FIG. 23.—HORIZONTAL DISTRIBUTION OF pH AT 300 M.

The high pH water, as represented by the 7.85 and 7.90 isolines, is almost non-existent; the 7.90 isoline occupies only a small area in the vicinity of Zanzibar, and the 7.85 isoline has also receded to the extreme south of the area.

*At 800 m. Depth (Text-fig. 26).*

The basic feature of distribution at this level is the complete predominance of low pH water in the entire area. In fact we see at this level the climax of the predominance of low pH water and the disappearance of high pH water. It seems that at this level the nucleus of the North Indian deep current is found. Although this current still shows



a division into three bands it is difficult to follow its movement further to the south as it becomes rather diffuse, but there is no doubt that at this level the North Indian deep current has a strong influence on the mass structure of the water.

The 7.65 isoline shows a wider expansion in the Gulf of Oman, along the coast of India and along the South Arabian coast. On the other hand, the 7.90 isoline has completely disappeared from the picture and the 7.85 isoline has receded to the extreme south between the Seychelles and the Carlsberg ridge.

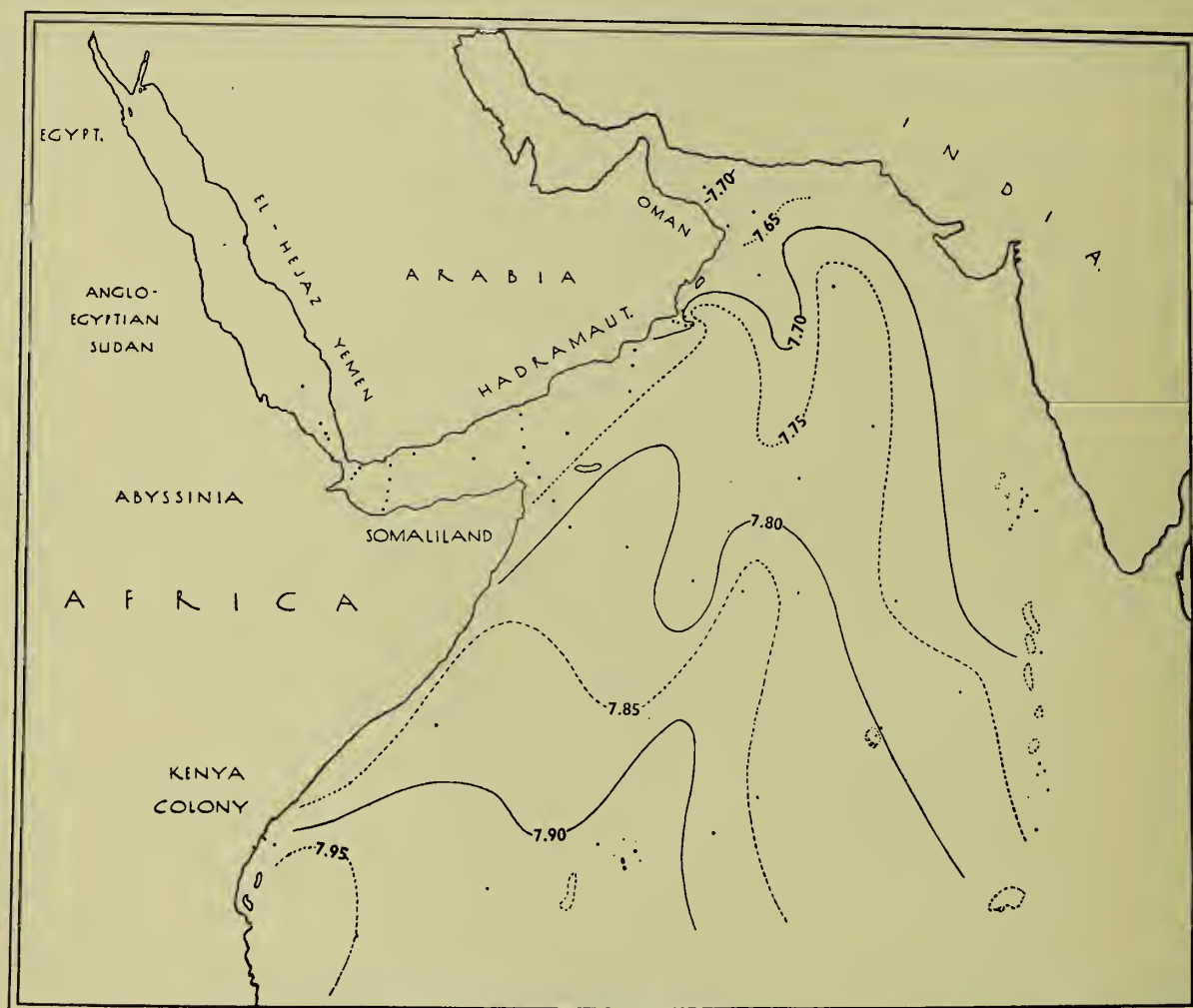


FIG. 24.—HORIZONTAL DISTRIBUTION OF pH AT 400 M.

*At 1000 m. Depth (Text-fig. 27).*

The distribution at this level is essentially similar to that for 800 m., but there are two important points of difference: (1) the entire disappearance of the 7.65 isoline, and (2) the fresh influence which the high pH water regains in the south, as shown by the more northerly position which the 7.80 isoline has now taken.

Considering the 7.80 isoline as representing the boundary between the low pH water from the north and the high pH water from the south, we find that the high pH water is

making a considerable advance to the north not only along the African coast but also in the eastern part of the area. Since this water approaches the area under consideration from the south it can be described, in the light of our knowledge of the circulation in the depths of the Indian Ocean, as the Antarctic intermediate current. We have already seen that similar water is found in varying degrees at the upper levels of 200–600 m., and in order to distinguish the two parts of this current from each other we have suggested designating them as the upper Antarctic intermediate current and the lower Antarctic intermediate current.

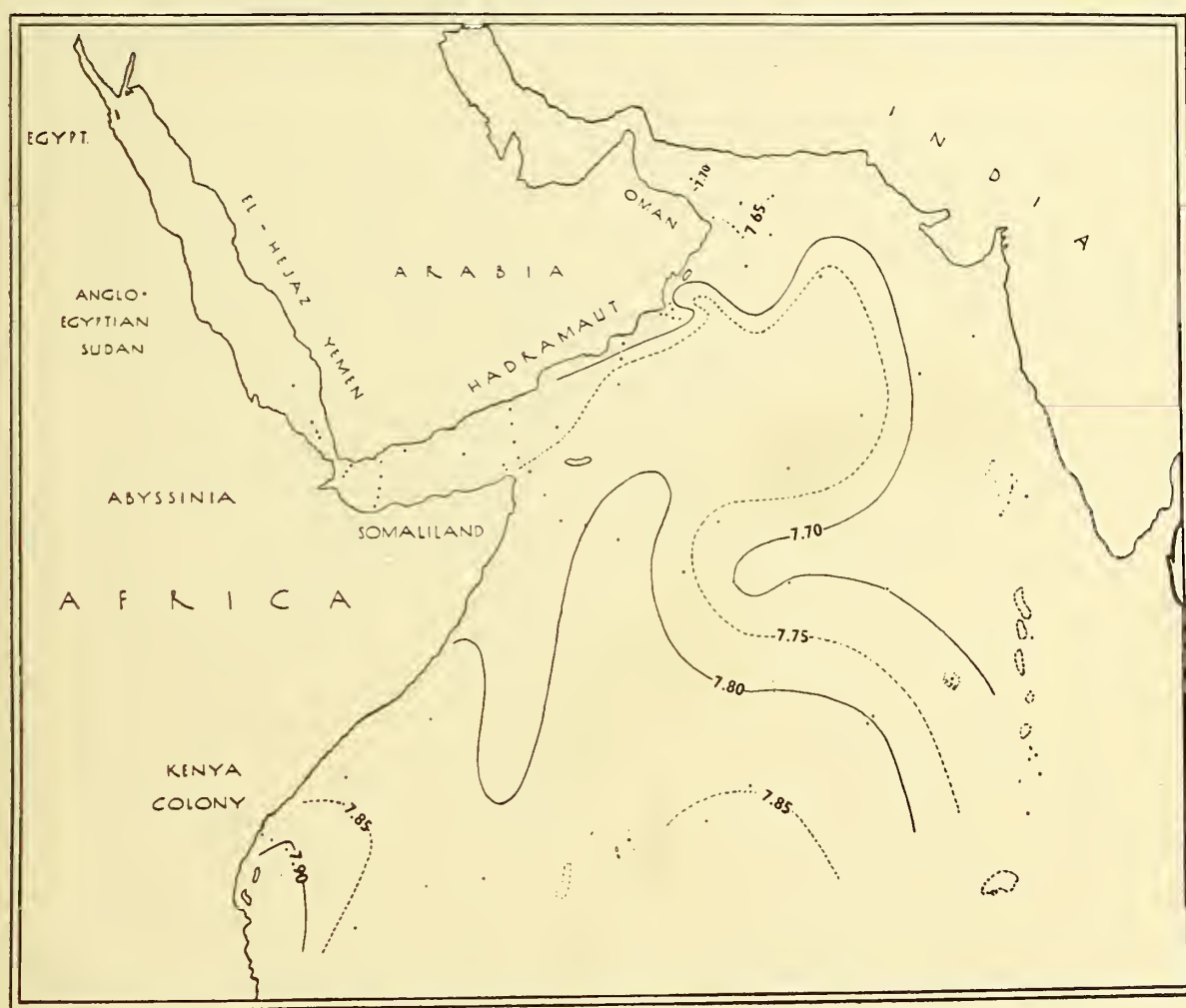


FIG. 25.—HORIZONTAL DISTRIBUTION OF pH AT 600 M.

The bands of the low pH water are seen at this level to have become narrower and to have receded to the north.

*At 1500 m. Depth (Text-fig. 28).*

As is seen in the chart, the water with high pH continues its advance northwards in three tongues. The central tongue, which is more pronounced than the other two, enters between the Seychelles and the Chagos Archipelago and moves in a north-easterly direction; the western one creeps along the African coast and the eastern one passes between the Chagos Archipelago and the Maldives.

The low pH water is now confined to the extreme north-east, although it still has a southern component penetrating between the central and western tongues of the lower Antarctic intermediate current.

*At 2000 m. Depth (Text-fig. 29).*

The most striking feature of distribution at this level is the disappearance of low pH water from the entire area; the 7.80 isoline is no longer present. The position of the

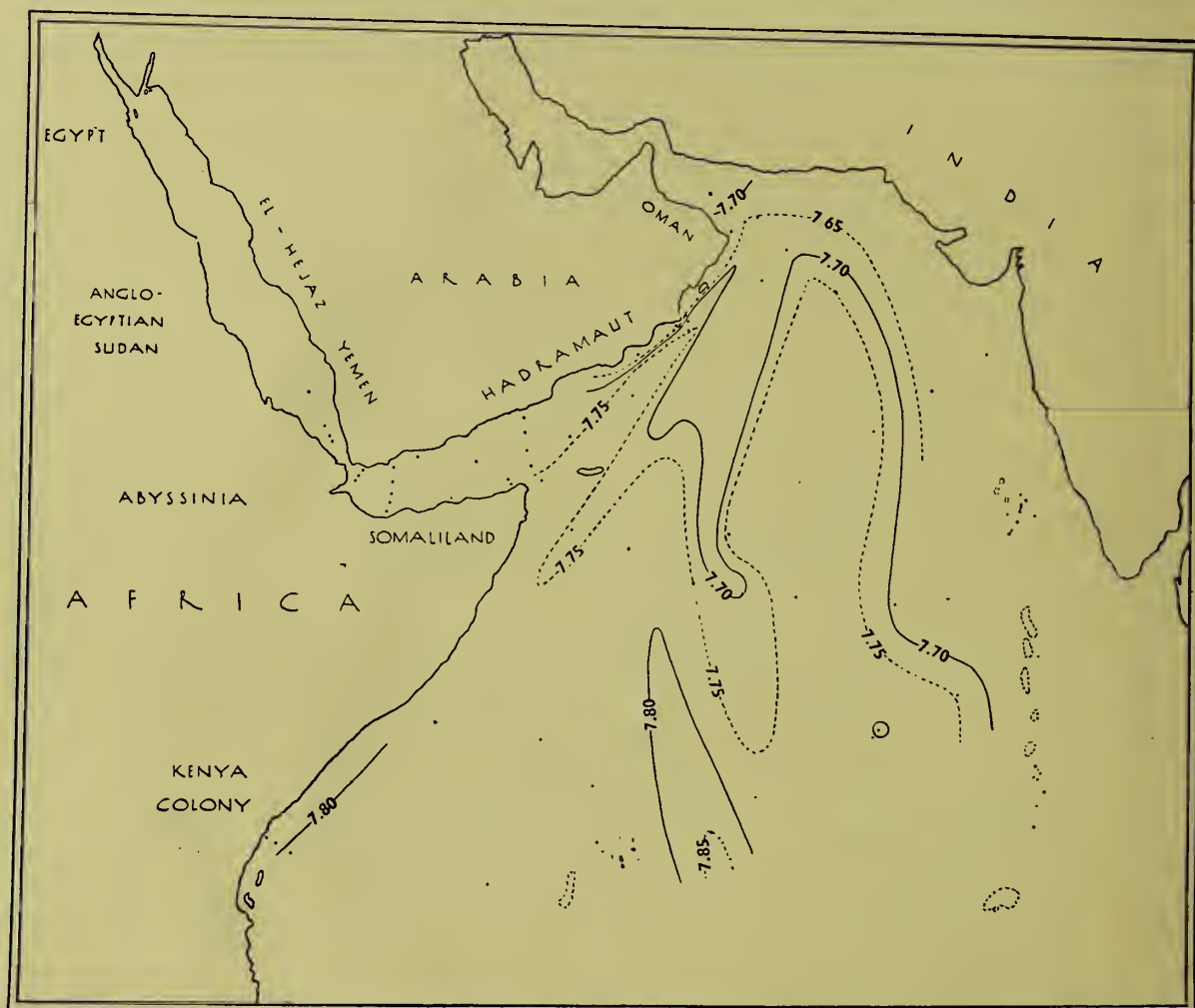


FIG. 26.—HORIZONTAL DISTRIBUTION OF pH AT 800 M.

7.85 isoline shows that the lower Antarctic intermediate current has spread north to the great depths of the Gulf of Oman. The appearance of the 7.95 and 8.00 isolines at this level gives the distribution picture a new feature.

*At 2500 m. Depth (Text-fig. 30).*

The distribution at this level is very similar to that at 2000 m. and calls for but little comment. The 7.90 and 8.00 isolines show a wider expanse to the north than at the previous level. The cause of the very high pH value found at Station 136, lying in the passage



between the Chagos Archipelago and Addu Atoll, is not clear. It is probably related in some way with local interaction with the floor of the ocean.

*At 3000 m. Depth (Text-fig. 31).*

The distribution at this level takes a more definite shape than at the previous level. This is due to a new topographical factor which asserts itself at this level, namely, the Carlsberg ridge which extends between the Chagos Archipelago and Socotra Island.

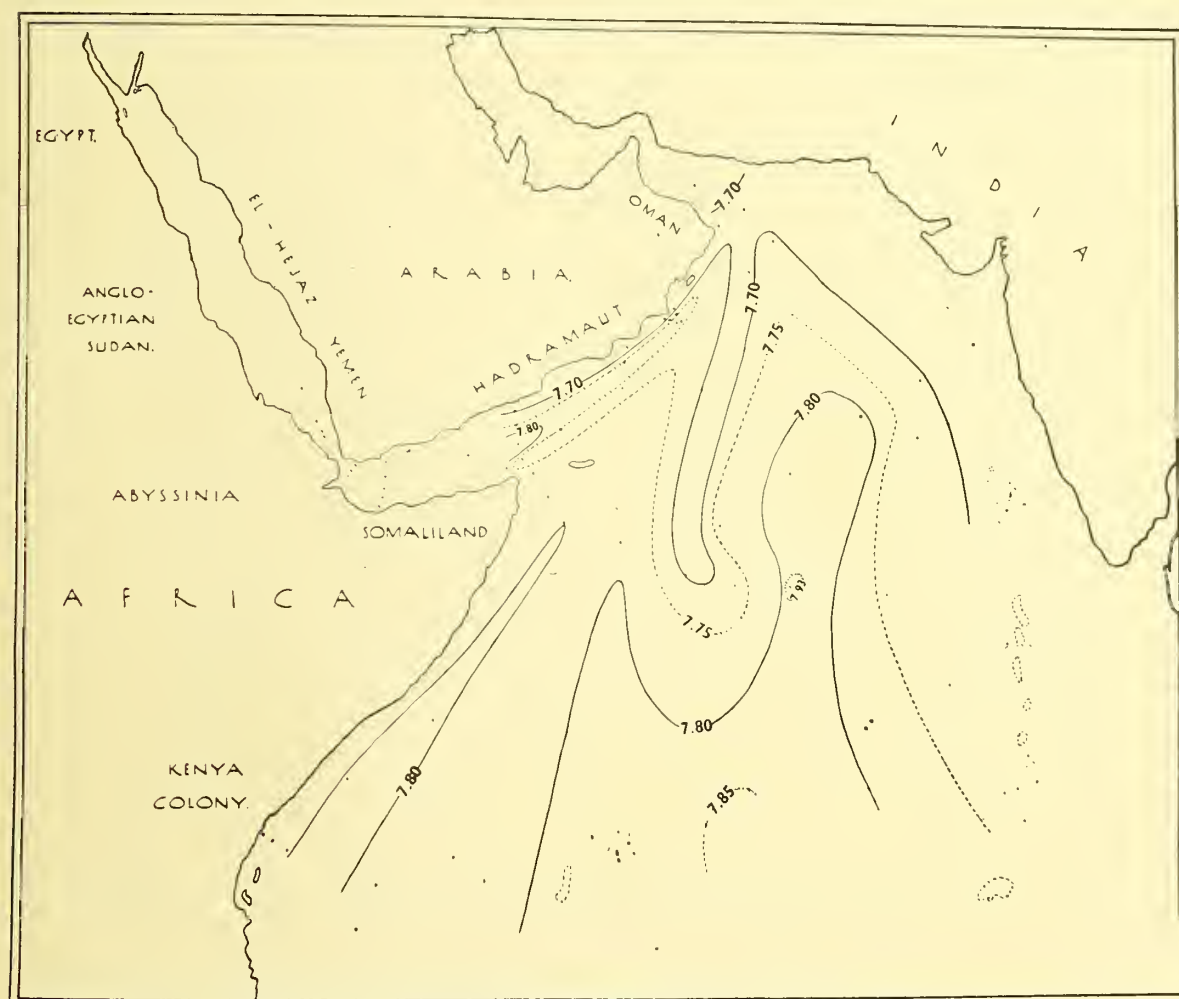


FIG. 27.—HORIZONTAL DISTRIBUTION OF pH AT 1000 M.

The water entering from the south shows a division into three branches. The eastern branch enters east of Carlsberg ridge between Addu Atoll and the Chagos Archipelago, the central one between the Chagos and the Seychelles and the western branch west of the Seychelles. Although there is no sharp transition between the pH values of the water at 2500 m. and the values at this level, the water here can be described, in the light of our knowledge of the deep circulation of the Indian Ocean, as the beginning of the Antarctic bottom current.

In the eastern branch of this current the pH decreases eastwards towards the Indian

coast, which decrease is probably due to admixture with overlying water with lower pH; but its increase in the region of the Arabian basin cannot be explained in the same way, since no water with such high pH values exists in the north. We have already put forward the explanation that the high pH values of this bottom water are acquired locally through interaction with the floor of the ocean. The high pH value found at Station 136 can be

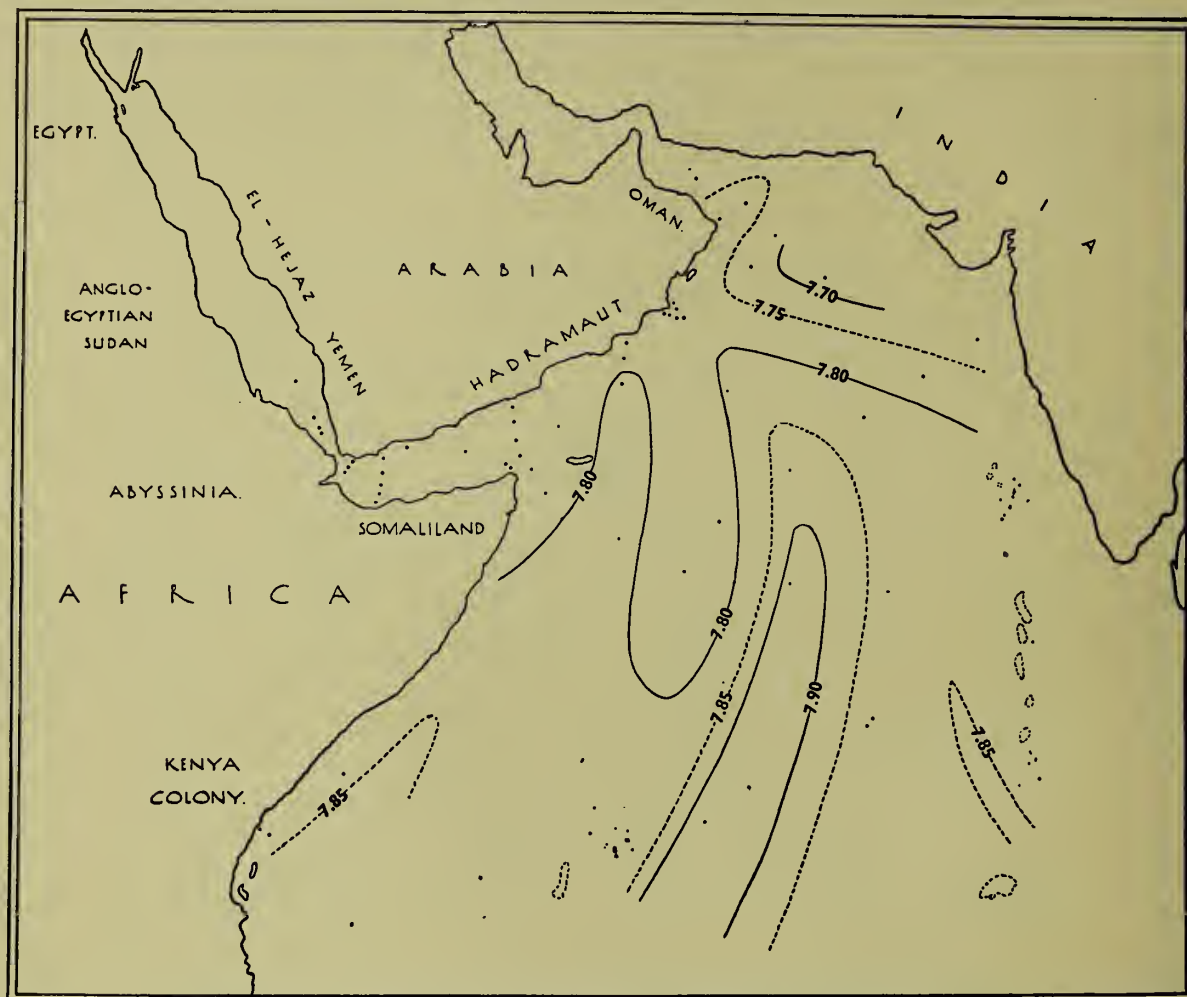


FIG. 28.—HORIZONTAL DISTRIBUTION OF pH AT 1500 M.

explained on similar grounds. The pH of the western branch decreases away from the African coast.

The 7.85 isoline has almost disappeared, but the 7.90 isoline extends north as far as the great depths of the Gulf of Oman.

*At 3500 m. Depth (Text-fig. 32).\**

The main features of distribution at this level are essentially similar to those at 3000 m. depth. The same division of the Antarctic bottom water into three branches is noticeable. The 7.85 isoline has now completely disappeared from the picture.

\* In this and the next Text-fig. the bottom contour is drawn to emphasize its relation to the Antarctic bottom current.

*At 4000 m. Depth (Text-fig. 33).*

This is the deepest level at which an appreciable number of observations was made. The water at this great depth shows the same threefold division revealed at 3000 and 3500 m. levels. The isolines have lost their stream-like character and it seems that there is little or no appreciable movement at this level. Only water with pH values higher than 7.95 is found at this depth, and the pH within each branch decreases eastwards.

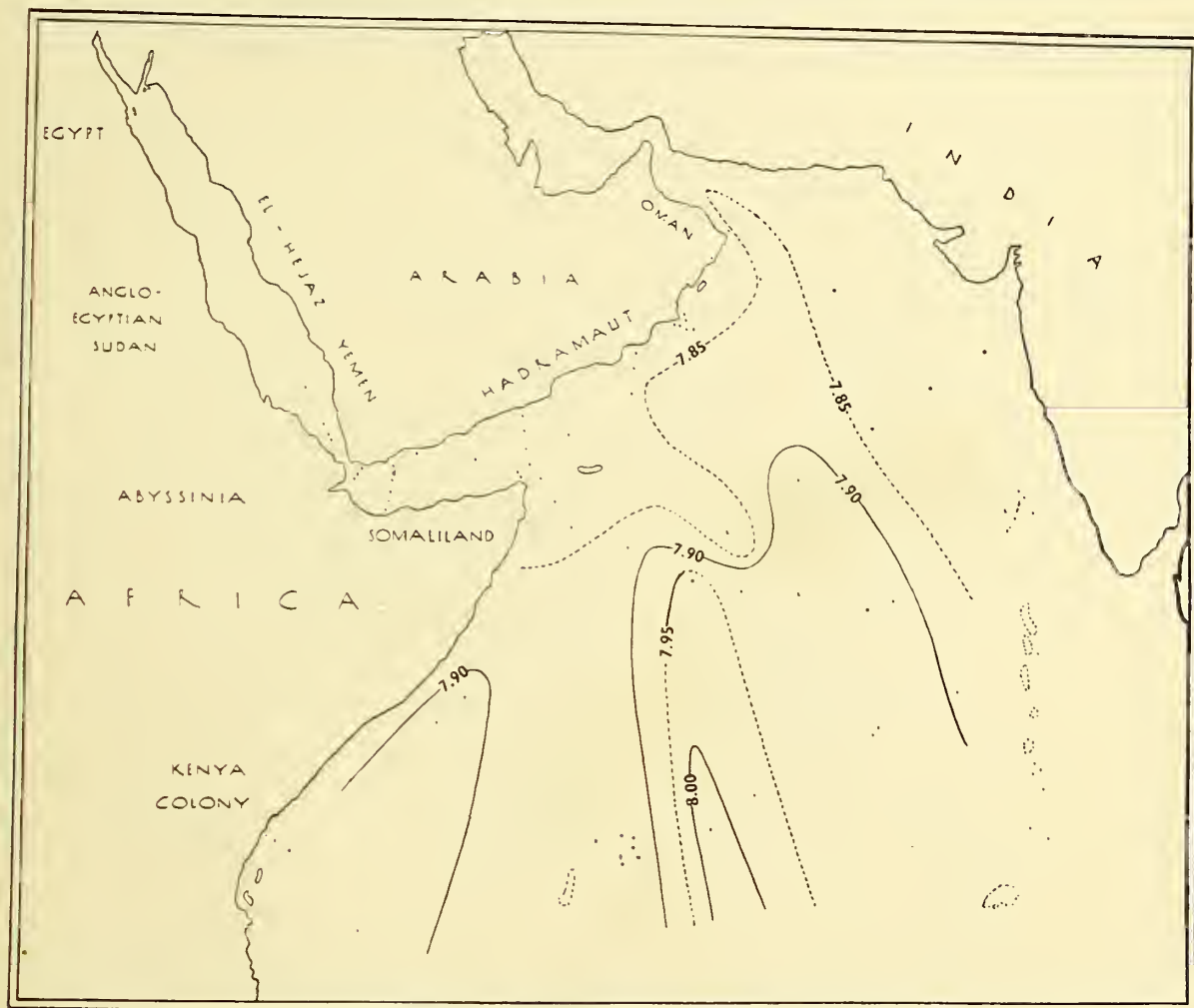


FIG. 29.—HORIZONTAL DISTRIBUTION OF pH AT 2000 M

### SHORT-PERIOD VARIATIONS OF pH.

The problem of vertical oscillations in the ocean has become of general interest in oceanography. The earlier investigations of Helland-Hansen and Nansen (1909) in the North Polar basin and the Norwegian Sea indicated that considerable vertical oscillations of the water-layers occur in the sea and that an occasional vertical series of oceanographical observations cannot therefore be taken as representative of the average conditions at any particular station. Later the same authors (Helland-Hansen and Nansen, 1926) discussed the problem anew and concluded that these vertical oscillations are probably connected



with the tides, strong evidence being found for 12-hour (lunar) and 24-hour periods. It was further discussed by Helland-Hansen (1930), by Defant (1932) and by several other investigators.

Bearing in mind that pH observations could not be expected to throw much light on this problem of vertical oscillations owing to irregularities caused by varying intensities of biological activity in the upper strata, which are partly the seat of these vertical oscilla-

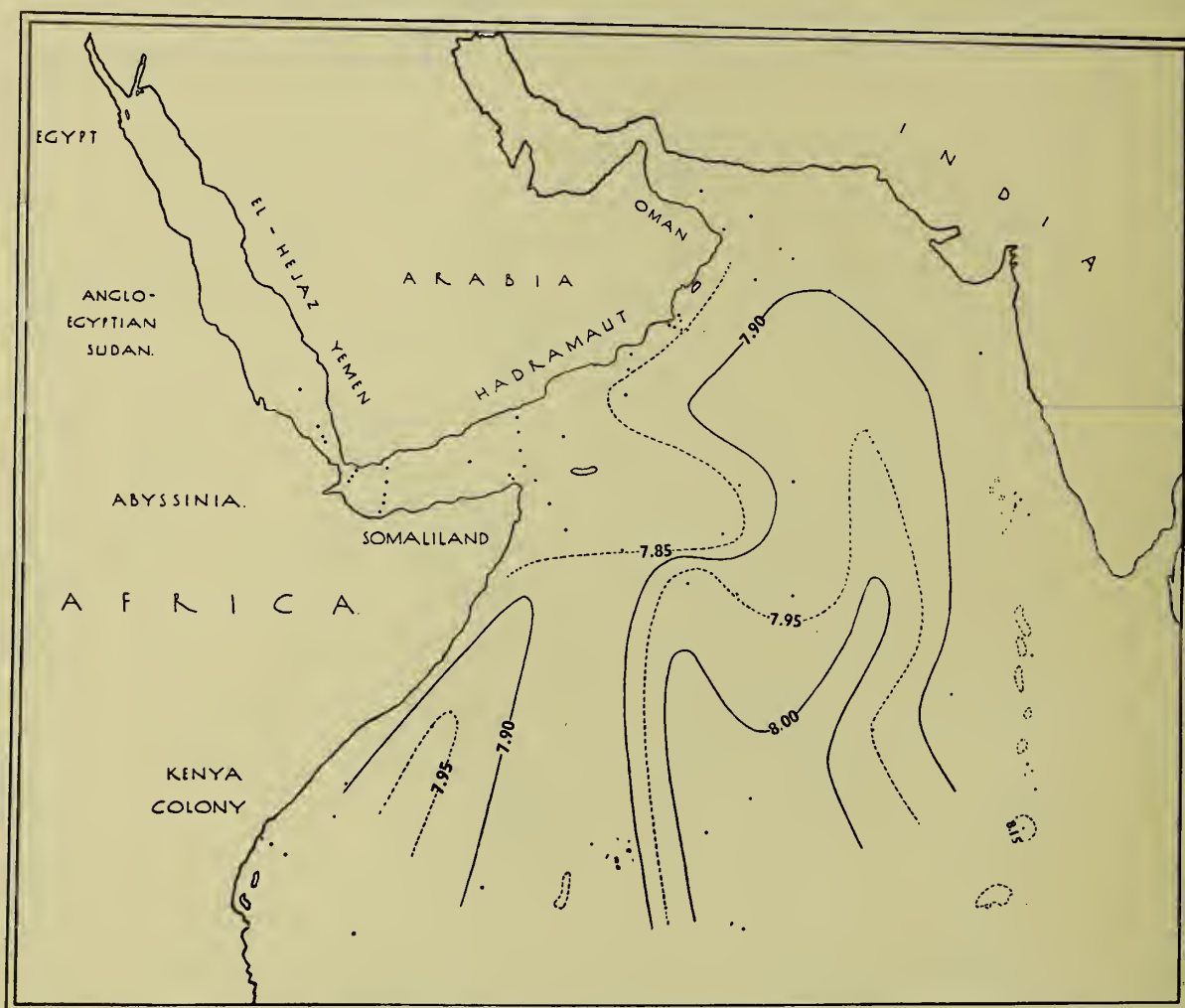


FIG. 30.—HORIZONTAL DISTRIBUTION OF pH AT 2500 M.

tions, short-period observations of pH were made with the sole object of finding how far these vertical oscillations are displayed by pH observations.

For this purpose observations of pH were obtained at intervals of roughly six hours at three stations in our area of investigation over periods varying from 12 to 24 hours. At Station 97 the period of observations extended over 18 hours, during which four series of observations were obtained at the usual depths from the surface down to a depth of 800 m.; the observations thus obtained are recorded under Stations 97A-97D. Owing to a mishap at Station 97D observations were, however, obtained down to a depth of 150 m. only. At Station 131 the period of observations extended over 24 hours, during which five similar series were made and the observations so obtained are recorded under Stations

131A-131E. At Station 145, which lies in Kardiva Channel, the period of observations extended over 12 hours, during which three series of observations were taken from the surface down to a depth of 400 m. only, the observations being recorded under Station 145A-145C.

To illustrate the nature of the short-period variations of pH, only observations obtained at Station 131 will be considered, as they extended over a relatively longer period. The pH observations at the depths of 0, 50, 100, 150, 200, 300, 400, 600 and 800 m. are plotted against time in Text-fig. 34.

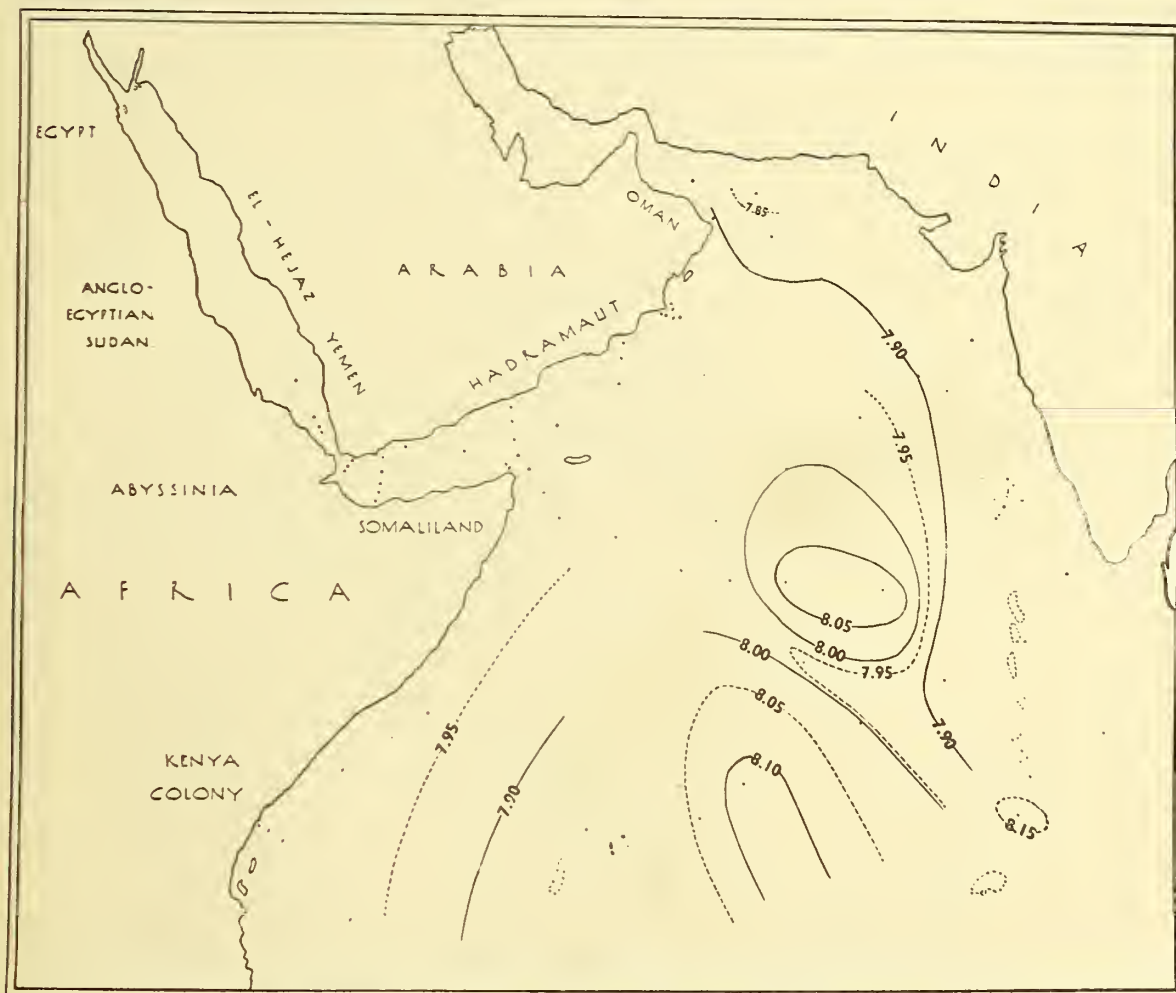


FIG. 31.—HORIZONTAL DISTRIBUTION OF pH AT 3000 M.

A satisfactory study of the short-period variations of pH is not possible on the basis of the present observations since they suffer from two drawbacks. In the first place they were carried out from the ship adrift, and secondly no special effort was taken to secure observations from the same depth at equal intervals of time. The curves represented in Text-fig. 34 show, however, that a considerable variation of pH takes place during the course of 24 hours.

The curves for the surface 50 and 100 m. depths show a steady increase in pH during the day time and a similar decrease during the night time. This is to be expected in the upper levels on account of photosynthetic activity during the day time, which causes the

pH to rise ; during the night time there would be an opposite effect. The curves for 150, 200, 300, 400 and 800 m. depths show similar features, which suggest a periodic character of these time variations of pH. The curve for 600 m. shows, however, at the time of observation at Station 131A a distortion, the cause of which is not clear or else it may be attributed to a horizontal displacement of the water-layers.

In view of these short-period variations of pH, the question now arises as to the representative quality of the serial observations of pH (and other serial oceanographic



FIG. 32.—HORIZONTAL DISTRIBUTION OF pH. AT 3500 M.

observations as well) and the significance of the conclusions derived therefrom. When the curves represented in Text-fig. 34 are examined, it is found that the maximum pH difference at any depth during the course of 24 hours does not exceed 0.10 pH unit. And since, in the construction of the vertical profiles and charts of horizontal distribution of pH, isolines were drawn at intervals of 0.05 pH unit and since the use of an interval of 0.10 pH unit would not have radically altered the pictures shown in the various profiles and charts, we can safely conclude that although the short-period variations of pH in the sea are startling, they would not affect to any considerable degree the significance of the conclusions which we have derived from the pH distributions.



## DISCUSSION.

In this section an attempt will be made to obtain, from our description of vertical and horizontal distributions, an insight into the general features of the hydrography of the north-western Indian Ocean and its adjoining waters and to interpret certain biological

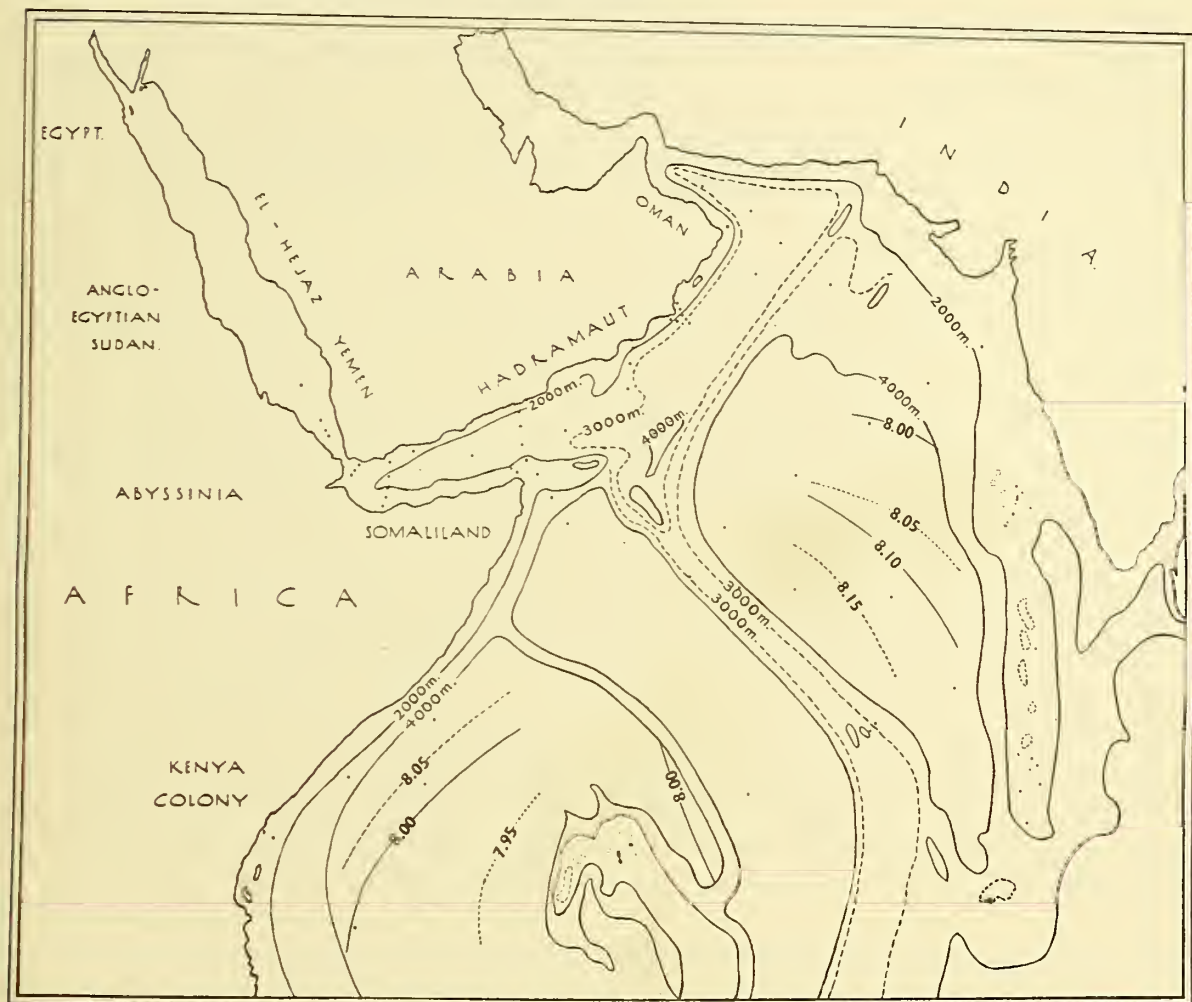


FIG. 33.—HORIZONTAL DISTRIBUTION OF pH AT 4000 M.

phenomena. As such an attempt would involve a reference to the general circulation of the Indian Ocean and its adjoining gulfs, we shall begin with a brief outline of our present-day knowledge of this circulation in so far as it has a close bearing on our area of investigation.

## HISTORICAL REVIEW OF THE CIRCULATION OF THE INDIAN OCEAN.

## WATER MOVEMENTS IN THE STRAITS OF BAB-EL-MANDEB.

The Red Sea is connected with the Gulf of Aden by the Straits of Bab-el-Mandeb; these Straits are 14 miles wide between Ras Bab-el-Mandeb and Ras Siyan and are divided by Perim Island into Large Strait and Small Strait. The deep part of the Red Sea is

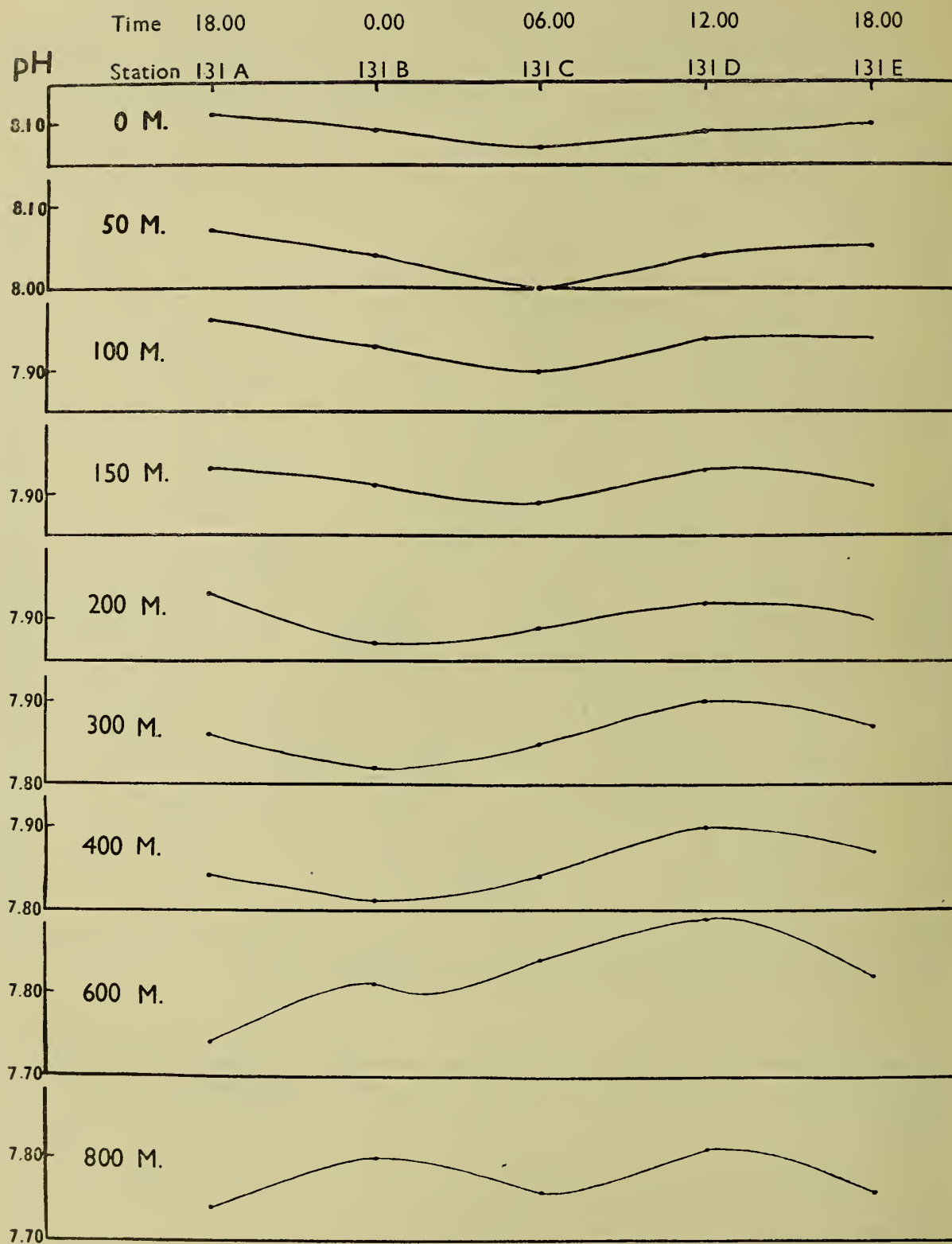


FIG. 34.—TIME VARIATION OF pH FOR VARIOUS DEPTHS AT STATION 131.

separated from the Gulf of Aden by a submarine threshold about 100 m. deep near Great Hanish Island.

The observations of salinity in the Straits of Bab-el-Mandeb made by Makaroff (1894) in the "Vitiaz" in March, 1889, constitute the first indication of the outflow of Red Sea water into the Gulf of Aden. He found that whereas the surface waters in the Straits had a salinity of  $36.1-36.5^{\circ}/_{\infty}$ , the deep water at a depth of 150 and 250 m. had a salinity of  $37.4$  and  $38.13^{\circ}/_{\infty}$  respectively.

The first attempt at a direct study of the water movements in the Straits of Bab-el-Mandeb was, however, made in 1890 by Capt. Usborne Moore in H.M.S. "Penguin" by means of a somewhat crude current meter (Wharton, 1898). Although the results showed that the lower strata did not run in the same direction as the surface strata, they were too ambiguous to afford more definite information.

The water exchange through the Straits of Bab-el-Mandeb was further shown by the salinity and temperature observations of the "Pola" in 1897-1898. Luksch (1898, 1901) concluded from these observations that light water flows from the Indian Ocean into the Red Sea along the Arabian side of the Strait and that more saline water flows out of the Red Sea through the western Strait at its great depths.

In January, 1898, Commander H. J. Gedge (1898) carried out successfully a series of current measurements in the Large Strait of Bab-el-Mandeb from H.M.S. "Stork". He used for his measurements a Pilsbury current meter, which had been improved after a series of experiments made by Capt. Usborne Moore in the English and Faroe Channels. On January 19th, 1898, the "Stork" was anchored in a depth of 215 m. about 7 miles S.W. by W. from Perim Island ( $12^{\circ} 34' 45''$  N.,  $43^{\circ} 17' 45''$  E.), and repeated observations were made during daylight for four days. Measurements were made at the surface, 9, 44, 91, 137 and 192 m. depths. As a result of these measurements the following conclusions were drawn: During the period of observation there was a permanent current at the surface setting into the Red Sea. At a depth of 192 m. there was a permanent current setting outwards at probably the same speed; both currents were influenced by the tidal streams. The dividing line between these two permanent currents was at a depth of 137 m., but the observations did not last long enough to define the position of this line with any precision.

The more recent Italian oceanographic exploration of the Red Sea has added considerably to our knowledge of the water movements in the Straits of Bab-el-Mandeb. In 1923-1924 extensive current measurements in the Straits of Bab-el-Mandeb were carried out from the surveying ship "Amiraglio Magnaghi" and from the vessel "Generale Arimondi". These measurements were made both in the Large Strait and in the Small Strait at a series of stations and their duration varied at different stations. For instance, at one station in the Large Strait measurements extended over a period of 14 days and at another station they lasted for about 8 hours only.

From his study of these current measurements, Vercelli (1925) came to the following conclusions: During the winter monsoon period there flows at the surface a current northwards from the Gulf of Aden into the Red Sea through the Straits of Bab-el-Mandeb. With increasing depth the direction remains the same, but the speed decreases until it reaches *nil* at about 100 m. Below this depth the current runs in the opposite direction, *i. e.* flows out of the Red Sea into the Gulf of Aden. The speed of this current increases with increasing depth until it reaches in the vicinity of the bottom values as high as those



of the north-going current at the surface. Both these currents are modified by the ebb and flow of the tide. Vercelli also reported that in the Large Strait temporary vertical oscillations take place in the transitional layer, *i. e.* in the layer between the Gulf of Aden surface current and the deep Red Sea current, and that these give rise to periodical variations in the temperature and salinity observable in the transitional layer. These thermo-haline oscillations were found to be connected with the rhythm of the tide, as has been found elsewhere (see, for example, Jacobsen and Thomsen, 1934).

The temperature and salinity observations of the "Amiraglio Magnaghi" in the Straits of Bab-el-Mandeb in 1923-1924 also bear out the existence of a deep Red Sea current flowing out of the Red Sea into the Gulf of Aden and a surface current flowing in the opposite direction (Vercelli, 1927).

In the spring of 1927 H.M.S. "Ormonde" made a line of five stations, running from the Straits of Bab-el-Mandeb into the Gulf of Aden, where temperature and salinity observations were taken. These observations proved (Matthews, 1927) the existence of the Red Sea outflow at all stations.

Schott (1929) summarized the results of oceanographical research in the Straits of Bab-el-Mandeb and concluded that the results establish the existence, along with the surface current which flows for the greater part of the year through the Straits of Bab-el-Mandeb to replace the loss by evaporation in the Red Sea, of a second deep current flowing in the opposite direction into the Gulf of Aden.

In 1929 further Italian investigations were carried out in the Red Sea on board the "Amiraglio Magnaghi" with the participation of the vessels "Lepanto" and "Porto Corsini". These investigations included current measurements in the vicinity of the Straits of Bab-el-Mandeb during the month of July. From these investigations Vercelli (1931) concluded that during the summer season there pass through the Straits of Bab-el-Mandeb three currents: A surface current (0-30 m.) from the Red Sea into the Gulf of Aden, a mid-current (40-150 m.) from the Gulf of Aden into the Red Sea, and finally a deep current (150 m. to the bottom) from the Red Sea into the Gulf of Aden.

Van Riel (1932) published some serial observations of temperature, salinity and oxygen which were taken by the "Snellius" in the southern Red Sea and the Gulf of Aden in April, 1929. These observations provide also valuable evidence of the outflow of the deep Red Sea water into the Gulf of Aden.

In a preliminary treatment of the temperature and halogen content observations of the present Expedition, Sewell (1934) pointed out that in September the water movements in the Straits of Bab-el-Mandeb differ from the results obtained by the "Amiraglio Magnaghi" in 1924, and the "Ormonde" in 1927 in the months of April and May. There were indications of at least three different strata of water in the Straits: A surface layer flowing out of the Red Sea into the Gulf of Aden; a mid-stratum, by far the largest of the three strata, flowing into the Red Sea between the depths of 70 m. and 160 m.; and a lower stratum, consisting of the bottom water of the Red Sea, which was small and scarcely passed over the sill. Sewell further showed that the observations in May agree with those of the "Amiraglio Magnaghi" and "Ormonde". It seems that at the time when Sewell published his preliminary notes he was not aware of the Italian investigations in July, 1929.

## GULF OF ADEN.

Information on the surface currents in the Gulf of Aden is amply given by the work of Matthews (1926) who discussed these currents in his report on the hydrographic observations made by H.M.S. "Sealark" and by ships trading in the Indian Ocean. But our knowledge of the deep currents in the Gulf, especially at its eastern end, was scanty prior to the John Murray Expedition.

The observation of a warm, highly saline deep current flowing out of the Red Sea into the Gulf was made in the past by the "Vitiaz", "Valdivia", "Pola" and "Stork", as we have already pointed out. New observations were made in the Gulf in 1924 by the "Amiraglio Magnaghi" (Vercelli, 1927) and in 1927 by H.M.S. "Ormonde" (Matthews, 1927). These observations confirmed the outflow from the Red Sea of a deep current which could be detected eastwards as far as the middle of the Gulf.

When Rafael de Buen (1927) expressed the surprising view that no Mediterranean water passes through the Straits of Gibraltar westwards into the Atlantic Ocean and that the Mediterranean deep current bends upwards at the sill and turns eastwards again, Schott (1929), in view of the fact that hydrographic conditions in the western part of the Gulf of Aden were thought to be similar to those in the Straits of Gibraltar, constructed a section extending from the southern end of the Red Sea to the longitude of Aden, showing the vertical distribution of temperature and salinity, as based on the observations of the "Pola", "Amiraglio Magnaghi" and "Ormonde". This section did not suggest at all that the deep current from the Red Sea bends upwards at the sill near Great Hanish Island and runs backwards into the Red Sea, as has been similarly suggested by Rafael de Buen to be happening in the Mediterranean, but, on the other hand, confirmed the outflow of a Red Sea deep current into the Gulf of Aden. Schott further pointed out that, in analogy with conditions in the Straits of Gibraltar, there is in the Gulf above this deep current, between 100 and 500 m. depths, a mass of water with low salinity which moves westwards with an axis at about 200 m. depth.

In his report on the observations of the "Ormonde", Matthews (1927) pointed out that the deep water below 1750 m. on the bottom of the Gulf at the most eastern station of the "Ormonde" has a temperature and a salinity similar to those of the water found at the same depths in the open ocean.

Van Riel (1932), reporting on the observations made by the "Snellius" in the Gulf of Aden, stated that seasonal changes in the hydrographic conditions in the Gulf of Aden would occur with the change of the monsoons.

Sewell (1934), in his preliminary report on the temperature and halogen-content observations of the present Expedition, suggested that the circulation at the eastern end of the Gulf is complicated and found that conditions are reversed in the different cruises in autumn and spring.

## GULF OF OMAN.

This Gulf is in open communication with the shallow Persian Gulf through the Straits of Hormuz; there is no submarine ridge between the two gulfs. With the exception of the description of the surface currents given by Schott (1918) very little was previously known about the hydrographic conditions in the Gulf of Oman. The temperature and



halogen-content observations of the present Expedition have suggested the efflux of a current from the Persian Gulf into the Gulf of Oman (Sewell, 1934).

#### THE CIRCULATION IN THE DEPTHS OF THE INDIAN OCEAN.

Our present-day knowledge of the hydrography of the Indian Ocean and its adjoining gulfs is derived mainly from the oceanographical observations of the "Challenger", "Gazelle", "Vitiaz", "Valdivia", "Gauss", "Planet", "Möwe", "Pola", "Sealark", "Investigator", "Amiraglio Magnaghi", "Ormonde", "Dana", "Snellius", "Mabahiss" and "Discovery II", and from other observations taken mostly by the surveying ships of the British Admiralty.

The first important contribution to our knowledge of the circulation of the Indian Ocean was furnished by the results of the "Gauss". In discussing the observations of the "Gauss" along a number of sections which extended northwards from the Antarctic across the southern Indian Ocean, Drygalski (1926) put forward evidence to show that in the southern Indian Ocean the water is stratified and that four water masses can be recognized, namely, the surface water, the polar water, the tropical water and the bottom water. According to Drygalski the surface layer can be traced from the south polar region as far north as lat.  $55^{\circ}$  S. Beneath this surface layer lies the polar water, which originates from the Antarctic and then moves in a north direction. North of lat.  $50^{\circ}$  S. it submerges and then flows at a depth of about 1000 m. to beyond the equator. Beneath the polar water is the tropical water which, because its temperature is higher than that of the water above and below it at the edge of the Antarctic shelf, and its salinity is also higher, Drygalski assumed to have originated in warmer seas in the north and to be flowing southwards. Finally the cold bottom water lies beneath the tropical water; this bottom water fills the bottom of the ocean to beyond the equator. According to Drygalski this bottom water is formed from a mixture of tropical and polar waters, but its mass is mainly derived from the tropical water, because this is quantitatively greater at the shelf edge than the polar water and its salinity is exactly or almost exactly the same as that of the bottom water. Drygalski assumed that the tropical water is cooled at the edge of the continental shelf through its contact with the polar water—occasionally also through climatic influences—and that it therefore becomes heavier and sinks to the bottom.

After the "Gauss" observations were published, Schott (1926) drew a meridional salinity section along long.  $60^{\circ}$  E. from Kaiser-Wilhelm Land to Socotra (from  $66^{\circ}$  S. to  $10^{\circ}$  N. lat.) which he based on the "Gauss" observations as well as on other available data. His section confirmed the fundamental pattern of the circulation in the Indian Ocean as put forward by Drygalski. Schott further emphasized the remarkable analogy between the stratification of the water masses and the deep circulation in the southern Indian Ocean and the Atlantic Ocean. This resemblance led Schott to the use of a nomenclature of the water strata analogous to that of the Atlantic Ocean. Besides the surface layer he distinguished the Antarctic intermediate current (Drygalski's polar water), the North Indian deep current (Drygalski's tropical water) and the Antarctic bottom water. He also indicated that the North Indian deep current is formed by the sinking of highly saline surface water from the Arabian Sea and adjoining gulfs.

In 1929 Dr. Lotte Möller published the results of a comprehensive investigation,



which was suggested and planned by A. Merz, into the circulation of the Indian Ocean. This investigation comprised the construction and description of four salinity and seven temperature sections. The construction of these sections was based on all available serial observations of temperature and salinity taken by various expeditions and ships during the period of northern winter—the north-east monsoon period. All these observations were reduced to modern standards and checked by means of the temperature-salinity correlation curves. This investigation included also the construction and description of twelve stream-lined monthly surface current charts for the area of the ocean north of lat.  $20^{\circ}$  S. The construction of these charts was based on the German, British and Dutch atlases of the currents of the Indian Ocean, as well as on the works of Michaelis (1923) and Töpelmann (1922).

From her discussion of the vertical distribution of temperature and salinity along the various sections, Möller gave a picture of the nature of the circulation in the Indian Ocean, showing the existence of four layers of water superimposed upon one another. The description, sources of origin and movement of these water strata can be summarized as follows :

(1) A warm upper layer, including the surface water, with high temperatures and salinities, known as the sub-tropical layer, and which is generally a few hundred metres thick.

(2) The Antarctic intermediate layer, composed of cooler and less saline water of Antarctic origin. This layer is formed by the sinking of cold Antarctic surface water under the warmer sub-tropical water in the region of the sub-polar convergence between lat.  $40^{\circ}$  and  $50^{\circ}$  S. This water then flows northwards, with an axis at about 1200 m. ; its course is not due north but is north-west at first and then north-east. At the end of its journey it rises and mixes with the water that feeds the North Indian deep current.

(3) The North Indian deep current—a mid-water layer, warm and with a high salinity. It is formed in the Arabian Sea and the north-western part of the Indian Ocean. Here there is great evaporation and the surface water of this part of the ocean, which consists of a mixture of sub-tropical and Antarctic intermediate waters, becomes denser, sinks downwards and flows southwards as the North Indian deep current. The outflow of water of high salinity from the middle depths of the Red Sea and the Persian Gulf into the Arabian Sea promotes the formation of this current. According to Möller this North Indian deep current flows south and traverses the whole ocean to lat.  $60^{\circ}$  S. beneath the Antarctic intermediate current. Near the south polar continent it rises, mixes with the thaw water along the edge of the land and then sinks again as the bottom current.

(4) The Antarctic bottom water, comprising cold water of Antarctic origin with low salinity, creeps northwards under the North Indian deep current, losing its characteristics on the way, so that near the equator it can scarcely be distinguished from the water above it. Its movement is dependent on the contour of the bed of the ocean.

Such is the picture of the circulation of the Indian Ocean as brought forward by the investigation of Möller. In its general features the picture still remains undisputed, though some of its details have been recently either questioned or elaborated.

On the basis of all available sources of bottom temperatures, Sewell (1932) constructed

a chart showing the probable course of the Antarctic bottom water from the south polar regions through the Indian Ocean to the north. The chart shows that the Antarctic bottom water drifts northwards in three main tongues, of which the eastern one can be traced into the Bay of Bengal, the second drifts into the Arabian Sea between the Chagos Archipelago and the Seychelles and the third or most westerly appears to end east of Madagascar.

Using the observations made by the "Dana" in 1929-1930, and by the "Snellius" in 1929, in the tropical and sub-tropical parts of the Indian Ocean, Thomsen (1933) showed that the North Indian deep current did not carry water with a salinity greater than 34.80 per mille south of a line from the northern end of Madagascar to Ceylon. He concluded, therefore, that Möller's assumption that the highly saline deep layer in the south was a continuation of the North Indian deep current could not be justified.

Möller (1933) disagreed with Thomsen and did not find in the new observations of the "Dana" and the "Snellius" enough justification for modifying her conclusions with regard to the North Indian deep current, and regarded the existing data as sufficient to show that this current flows southwards as far as the Antarctic regions and that the failure of the "Dana" and "Snellius" observations to indicate the existence of this current is probably due to great fluctuations in its salinity owing to similar variations in the salinity of the coastal waters.

New light was thrown on this controversial question by the observations of R.R.S. "Discovery II" in 1935. On her voyage from the Antarctic the "Discovery II" made a series of stations on a line from Marion Island through the Mozambique Channel to the Gulf of Aden. A preliminary examination of these observations by Clowes and Deacon (1935) showed that although the North Indian deep current could be detected (from its high salinity of 34.80 ‰) as far as 20° S., the highly saline water found in the south-western part of the ocean as far north as 50° S. is not its continuation. The temperature and oxygen content of this latter water suggested that it belonged to an eastward movement of the Atlantic deep current, as was suggested by Merz and Wüst (1922). Further, the oxygen distribution along the "Discovery II" section suggested that the North Indian deep current did not come to a sudden termination at latitude 20° S. and indicated that it can be traced much further south as a tongue of poorly oxygenated water sandwiched between Antarctic intermediate water and an eastward current of Atlantic deep water. Clowes and Deacon also suggested that the volume and salinity of the north Indian deep current might be subject to large variations, probably related to the change of salinity in the coastal regions and to the current differences brought about by the changes of the monsoon winds and variation in the south equatorial current.

Wüst (1935) came to the same conclusion as that reached by Clowes and Deacon regarding the Atlantic origin of the high salinity deep water in the south-western Indian Ocean.

Later, Thomsen (1935) made a further study of the "Dana" and "Snellius" observations by constructing temperature-salinity correlation curves. From his analysis of these curves Thomsen showed that in the Indian Ocean there can be distinguished seven water strata. He pointed out once more that the North Indian deep current was not found to flow at a depth of 2000-3000 m. south of a line between Ceylon and Cape Delgado, but that it is possible that a rudimentary, southerly-directed current, with a nucleus at about 1200 m., exists south of this line. Thomsen also reached the conclusion that the bottom water in the



Indian Ocean results from mixing between the Antarctic bottom water and the eastward drift of the Atlantic deep water. He also pointed out that the Antarctic intermediate current mixes on its way northwards with the over- and underlying waters, and that it rises nearer to the surface as it advances north. With regard to the fate of the water carried north by this current and also by the bottom current, Thomsen stated that it is not improbable that this water wells up to the surface and mixes slowly with the surface water to serve as a compensation for the loss due to evaporation in the northern regions.

Having briefly reviewed our present-day knowledge of the deep circulation in the north-western Indian Ocean and its adjoining gulfs, we are now in a position to discuss the significance of, and to draw some conclusions from, the distribution of pH.

### CONCLUSIONS.

#### THE pH-DEPTH CURVE.

The long-held view, first put forward by Palitzsch (1912), that the pH decreases continually with increase of depth in the sea is now known to be incorrect, and should be abandoned in view of the modern precision of pH measurement and the application of the corrections which this measurement involves.

The pH of any water mass is determined by its carbonic-acid equilibrium, which not only depends on its origin, but is influenced to varying degrees in the upper levels by planktonic activity, in the great depths by oxidation and geochemical processes and at the boundaries where it meets other water bodies by mixing. It is, therefore, evident that the shape of the pH-depth curve in any oceanic region is determined by the pH of the various water masses constituting the sampled water column.

Gaarder (1927) found that the pH-depth curve in the north-eastern Atlantic exhibits a peak below the surface due to a maximum of phytoplanktonic activity. Seiwel (1931) showed that the pH-depth curve in the north Atlantic exhibits an increase of pH near the bottom when the pH values are corrected for temperature. The "Meteor" observations in the South Atlantic provided abundant evidence to disprove Palitzsch's view (Wattenberg, 1933). Our pH observations in the north-western Indian Ocean and its adjoining gulfs provide similar new evidence, which is partly seen at a glance from Text-fig. 2, where several pH-depth curves are represented.

#### WATER MOVEMENTS THROUGH THE STRAITS OF BAB-EL-MANDEB.

*The winter monsoon period.*—Our observations of pH in May, at the end of the winter monsoon period, confirm the conclusions already arrived at by the direct measurements of H.M.S. "Stork" in January (Gedge, 1898), and by the "Amiraglio Magnaghi" in March–April (Vercelli, 1925), with regard to the water movements in the Straits of Bab-el-Mandeb.

During the winter monsoon period there pass northwards through the Straits of Bab-el-Mandeb a surface current from the Gulf of Aden and a deep current in the opposite direction out of the Red Sea. According to the "Stork" measurements (January) the separating boundary between these two currents lay at about 137 m.; according to the "Amiraglio Magnaghi" measurements (March–April) it lay at about 100 m.; and according to our observations it lay at a depth of about 50 m. It seems, therefore, that the volume of the surface current gets less and less as the winter season approaches its end.

With regard to the water exchange through the Straits during the winter monsoon period, our pH observations bring to light the fact that the bottom Red Sea water is not



involved to any great extent in the water exchange, and that the outflowing current consists almost entirely of mid and deep Red Sea waters. This is the reason why we have spoken of the outflowing current during this period as the Red Sea *deep* current.

*The summer monsoon period.*—Observations of pH at the end of the summer season lead to conclusions with regard to the water movements through the Straits of Bab-el-Mandeb which agree very well with the direct measurements made by the “Amiraglio Magnaghi” in July (Vercelli, 1931).

During the summer monsoon period there pass through the Straits of Bab-el-Mandeb three currents, of which the middle one, which constitutes the bulk of the water column in the Straits, flows from the Gulf of Aden into the Red Sea with a nucleus at about 80 m. The upper and bottom currents flow out of the Red Sea into the Gulf of Aden.

The above summary constitutes the facts of the *régime* of currents through the Straits of Bab-el-Mandeb during the two monsoon seasons. When we seek an explanation of these seasonal changes in the currents we find that the following factors have to be taken into consideration :

(1) The seasonal changes of the monsoons ; during the north-east monsoon period the prevailing wind in the southern part of the Red Sea is S.S.E., whereas it is N.N.W. during the south-west monsoon period.

(2) The seasonal variation in the sea-level in the Red Sea as a whole ; according to the Admiralty Tide Tables, Part II, the sea-level is relatively lower at Suez than it is at Perim during the summer months, whereas it is relatively higher at Suez than at Perim during the winter months.

(3) The difference in density of the waters in the Red Sea and in the Gulf of Aden which gives rise to a gradient current.

(4) The alternating periodic motion of tidal currents through the Straits.

Disregarding the effect of the tidal currents, we should expect, in the light of the above facts, both from density-gradient and wind-effect points of view, a surface current (the resultant of wind-effect and density gradient) to flow from the Gulf of Aden into the Red Sea during the winter monsoon period. This we have found to be actually the case, and, in compensation, a deep current flows out of the Red Sea. The balance between the inflow on the one hand and the outflow plus water loss by evaporation on the other seems, however, to be unattained in this season, and as a result water accumulates in the Red Sea and a general rise in the sea-level above the mean sea-level takes place.

Disregarding again the influence of the tidal currents, we find that in the summer months, under the dominating influence of the wind, a surface current flows out of the Red Sea into the Gulf of Aden.

Hence we come to a very important conclusion, namely, that the *régime* of currents through the Straits of Bab-el-Mandeb is determined mainly by the seasonal change in the winds and that other factors are of secondary importance in this respect.

It seems, again, that during the summer months the balance is not attained, the water loss by evaporation from the Red Sea plus the outflow into the Gulf of Aden being in excess of the inflow from the Gulf of Aden. Hence we get a general lowering of the sea-level below the mean sea-level in the Red Sea.

In presenting the above arguments we have disregarded the influence of the tidal streams, since it is evident that these streams would influence the speed of the wind-driven current only periodically. To what depth this influence extends and whether it reverses

at times the direction of the wind-driven current are questions on which our observations cannot throw any light.

#### THE WATER MASSES IN THE GULF OF ADEN.

A general scheme of the circulation in the Gulf of Aden has not yet been formulated. Here we shall confine ourselves to a description of the various water masses in the Gulf as revealed by our pH observations. This may contribute towards the formulation of such a scheme.

*Conditions in May.*—From a pH standpoint we can distinguish in the Gulf of Aden during May four water strata :

(1) The surface layer, which varies in thickness from 50 to 100 m., has a westerly movement under the influence of the prevailing wind.

(2) Below the surface layer is a sub-surface stratum, characterized by low pH values, which extends down to a depth of 400 m., and has an axis at a depth of about 200 m. At the western end of the Gulf the thickness of this stratum gets smaller. Observations along Section E have suggested that this layer might be an offshoot of the Antarctic intermediate current, but this suggestion cannot be much emphasized owing to the limited number of observational stations at the eastern end of the Gulf.

(3) Beneath this sub-surface layer is the outflowing Red Sea deep current, characterized by relatively high pH values. This current has an axis at a depth of 600–800 m. in the west and at 800–1000 m. eastwards.

(4) Finally, there is the bottom water of the Gulf. Observations along Section E indicated the possibility of this water originating in the Indian Ocean south of the Socotra-Guardafui ridge, but it has not been possible to trace it any further in the open ocean.

*Conditions in September–October.*—Although the observations made in September came at the time of the change of the monsoons and those made in October came at the beginning of the winter season and, therefore, fell with those made in May in the one and the same season, these observations reflect, nevertheless, the relics of the summer conditions.

With the exception of the eastern part of the Gulf, where conditions appeared somewhat complicated during September–October, we find in the greater part of the Gulf the fourfold arrangement of water strata. The thickness of the various strata and their pH values are somewhat different during these months.

The surface layer is less thick and is sharply separated by well-pronounced pH gradients from the layer below it, which we have seen to move in the opposite direction towards the Red Sea as a compensating current. Beneath this layer is the water mass representing the outflowing Red Sea bottom current; its volume is smaller and its pH is higher than in May. Finally, there is the bottom water of the Gulf, the volume of which is larger in these months.

The above conclusions with regard to the differentiation of the water masses in the Gulf of Aden agree fairly well with deductions made by other investigators. The westward movement of a sub-surface water mass between 100 and 500 m. with an axis at about 200 m. has been suggested by Schott (1929) from his discussion of the “Amiraglio Magnaghi” and “Ormonde” observations as has been already pointed out. The flow of the deep Red



Sea water eastwards into the Gulf of Aden has been observed by various expeditions. And, finally, Matthews (1927) suggested that the bottom water in the Gulf of Aden is of oceanic character.

#### THE DEEP CIRCULATION OF THE NORTH-WESTERN INDIAN OCEAN.

*The North Indian deep current.*—Our description of the vertical and horizontal distributions of pH off the South Arabian coast, in the Gulf of Oman and off the coast of India have thrown new light on the principal sources of the so-called North Indian deep current. As we have already seen from the review of our present-day knowledge of the deep circulation of the Indian Ocean, Schott and Möller made the assumption that this current is formed in the Arabian Sea, where, owing to evaporation, the surface water becomes denser, sinks downwards and then flows southwards. The properties of this current, high temperatures and salinities and low oxygen-content, are well-known (Clowes and Deacon, 1935). Since an examination of the oxygen data of the present Expedition shows that the minimum pH layer in these coastal regions of the Arabian Sea is also poorly oxygenated and that the reduction in oxygen-content within this layer stands in close relationship to the decrease in pH, it is self-evident that the minimum pH layer in these regions is the North Indian deep current itself.

In our description of the vertical distribution of pH we have established again and again the following characteristics of the minimum pH layer in these coastal regions :

- (1) Firstly, it lies immediately below the surface layer and is separated from it by well-pronounced vertical pH gradients.

- (2) Secondly, it attains a great thickness in these regions and possesses relatively low pH values.

- (3) Finally, its upper boundary shows a closer approach to the surface than it does anywhere else in the north-western area of the Indian Ocean.

To account for these characteristics of the minimum pH layer it is necessary to consider a number of physical, chemical and biological conditions of the waters of these regions.

- (1) Owing to the prevailing high surface temperatures of these waters in the winter months, evaporation renders the surface water denser and causes it to sink and lose contact with the atmosphere. The particles of such water sinking from the surface will obviously carry with them any oxygen which they contain

- (2) In spite of the fact that our observations in these coastal regions were made when the winter season had already begun, an examination of the temperature observations reveals, nevertheless, the presence of a distinct temperature gradient in the upper levels not far from the surface. This gradient was found to be more marked at the end of the summer season off the Arabian coast in the Gulf of Aden, where a drop of about 12° C. in temperature occurred between the surface and the depth of 50 m. It is probable that similar gradients occur in the summer in these coastal regions of the Arabian Sea as well. The development below the surface of a layer with a maximum temperature gradient (the so-called thermocline or discontinuity layer) during the summer gives rise to marked density gradients, notwithstanding the increase of surface salinity due to evaporation. Such a state of stability hinders mixing across the discontinuity boundary, so that the underlying water receives little or no oxygen from above. Its oxygen-content is gradually exhausted by processes of organic oxidations, the accumulation of



carbon dioxide being revealed by the low pH values. The development of a marked density gradient near the surface would also cause the decomposition of sinking organic matter (of similar specific gravity) to occur at a higher horizontal level than in regions where such a gradient is less marked or absent (Seiwell, 1934), a feature which results in an increase in the thickness of the minimum pH layer. A third possible effect of this sharp transition in temperature might be the death which it inflicts on planktonic organisms which happen to come in the sphere of influence of the transitional zone. On the whole, such decomposition processes which take place in the immediate neighbourhood of the surface should give rise to distinct vertical pH gradients.

(3) These processes of organic oxidations are further promoted by two other factors, namely, the relatively high temperatures within the minimum pH layer, which make possible a higher rate of oxidation, and the availability of organic matter. With regard to the latter factor, the work of Gilson (1937) on the nitrogen cycle in these waters clearly indicates that such coastal regions are much richer in plankton than the open ocean. The high surface values of pH observed in these regions also suggest a higher activity of the phytoplankton than in the open ocean. The sinking of this plentiful plankton after death would supply organic matter in abundance for the maintenance of organic oxidations.

It is thus seen that whereas the origin of the North Indian deep current is connected with the strong evaporation during the winter in the coastal regions of the Arabian Sea, the properties of low pH and low oxygen-content, which characterize this water mass and indicate its source, are due to intense organic oxidations taking place in these coastal regions on account of the development of a sharp thermocline in the summer. It is noteworthy that the zone between the depths of 83–102 m. and 1253–1536 m., in which there is a complete absence of life, a fact revealed by the present Expedition's trawling and dredging (Sewell, 1934), corresponds remarkably well with the limits of the minimum pH layer.

It is on account of the low pH character of the North Indian deep current that it has been possible to trace its movement and to define its position in the water column. Off the South Arabian and Indian coasts it lies immediately below the surface layer, but further west it is separated from it by the upper Antarctic intermediate current; off the African coast it is practically non-existent. The description of the horizontal distribution of pH has shown that this current, which exhibits a threefold division in the upper levels, tends to move south-westwards on account of the deviating force of the earth's rotation and that it sinks to greater depths on its way south until it reaches its greatest expanse at a depth of 800 m.\* Moreover, the horizontal distribution of pH suggests, though the pH observations did not extend much south of the equator, that there is a tendency for this current to lose its distinctive character farther south.

Although the observations in the eastern approaches of the Gulf of Aden are too far apart to enable any precise statement to be made regarding the part played by the Red Sea water in the formation of this current, the author is inclined to suggest that the

\* The suggestion made by Sewell (1934) with regard to the continuation of the North Indian deep current at a depth of 2500 m. in the position of Station 166 is unjustified, since the relatively high value of halogen-content ( $19.50^{\circ}/_{\infty}$ ) assumed to occur at this depth has been found, from a consideration of the depth of sampling as measured by the thermometric method, to be misleading.

principal sources of the North Indian deep current are confined to the South Arabian and north-western Indian coastal regions, and that on the basis of pH observations the Red Sea water does not seem to contribute any significant proportion to the formation of the North Indian deep current. There is, therefore, no justification in giving the Red Sea water such a prominence in the characterization of the water masses in the Indian Ocean as was done by Thomsen (1935).

*The Antarctic intermediate current.*—The water, characterized by pH values intermediate between the high values of the surface layer and the low values of the minimum pH layer, has been assumed to correspond with the Antarctic intermediate current. This current originates in the Antarctic regions and approaches the area under consideration from the south.

In the eastern regions of the area investigated this current lies below the North Indian deep current. In the central and western regions it is split up by the North Indian deep current into two portions, which we have designated as the upper and lower Antarctic intermediate currents; in these regions the upper Antarctic intermediate current lies below the surface layer and above the North Indian deep current. Off the African coast the Antarctic intermediate current shows no splitting owing to the absence of the North Indian deep current.

The horizontal distribution of pH has shown that the Antarctic intermediate current enters the area of the north-western Indian Ocean mainly on the western side. It tends then to move north-eastwards on account of the deflective force of the earth's rotation, rising nearer to the surface on its way north. In the position of Station 40 the upper Antarctic intermediate current divides into an easterly and a westerly branch, the latter moving towards the Gulf of Aden. It is suggested that this upper Antarctic intermediate current, with its possible rich stores of nutrient salts, is responsible for the higher activity of plankton and its outburst in the coastal regions of the Arabian Sea.

The lower Antarctic intermediate current spreads widely at a depth of 2000 m. and reaches as far north as the Gulf of Oman. Indications of upwelling of this current in the central regions of the Arabian Sea have been shown by the vertical distribution. Both the upper and lower Antarctic intermediate currents show at certain levels a threefold division complementary to that of the North Indian deep current.

*The Antarctic bottom current.*—The depths of the north-western Indian Ocean below 3000 m. are filled with the Antarctic bottom water, which originates in the Antarctic regions and drifts northwards. On account of the topographical obstruction imposed by the Carlsberg and the Seychelles ridges, this water enters the area under consideration in three streams, the eastern one entering between Addu Atoll and the Chagos Archipelago, the central one between the Chagos Archipelago and the Seychelles, and the western one west of the Seychelles.

It is suggested that the exceptionally high pH values shown by this water, especially in the Arabian basin on the north-east side of the Carlsberg Ridge, are possibly due to local interaction with the floor of the ocean.

It is thus seen that the above conclusions throw further light on the origin, character and movement of the water masses in the north-western Indian Ocean and agree in some degree with the deductions made by other investigators. These conclusions should prove of some aid to the understanding of the distribution of life and its conditions in the area investigated.



We now turn to the consideration of certain biological and geochemical aspects of the pH distributions. The importance and usefulness of pH observations in these fields of study have been brought forward in a comprehensive review by Labbé (1932).

#### THE ACTIVITY OF THE PHYTOPLANKTON.

A survey of the present state of our knowledge of the physical and chemical factors governing the production of phytoplankton in the sea is given by Gran (1932), and recently by Gilson (1937). The conditions for the production of phytoplankton in the north-western Indian Ocean as revealed by the nitrate and nitrite distributions in conjunction with the oxygen, stability, transparency and phytoplankton data of the present Expedition have been discussed in detail elsewhere in this volume by H. C. Gilson (1937). We shall confine ourselves here to summing up, in the light of our knowledge of the oceanic circulation deduced above, a few conclusions regarding the activity of the phytoplankton as brought about by our pH observations in the same area.

From the description of pH distributions we have seen that the highest pH values of the surface waters are found in the north-eastern area of the Arabian Sea and off the African coast. These values have been considered to signify a higher photosynthetic activity which might be due either to an abundance of phytoplankton or to an increased rate of photosynthetic processes. The theory developed by Brandt (1899, 1902 and 1920), according to which the productivity of the sea is limited by the supply to the surface layers of the necessary nutrient salts, is generally accepted. Both the maintenance of a large phytoplanktonic population and the rapidity of photosynthetic processes would therefore necessitate, amongst other conditions, a sufficient supply of nutrient salts.

The view has been put forward that coastal waters are relatively more productive than the open ocean on account of the influx of nutrient salts from the land ; but doubts have been cast on the correct uses of this view by Gilson (1937) ; and such a source must be insignificant or practically lacking in the area under investigation. Another possible source of supply of these salts is the upwelling of deep water, the immediate effect of which is to reduce the surface temperature and salinity. Evidence of this phenomenon exists for the African coast only (Matthews, 1926) ; observations of temperature and salinity at Station 22 of the present Expedition seem to give similar evidence.

In general, conditions off the African coast seem to favour the activity of the phytoplankton. Thus the Antarctic intermediate current, which rises towards the surface from greater depths as it moves north along this coast is bound to be rich in nutrient salts. On account of the instability of the upper part of the water column in this region this current mixes easily with the surface water and enriches it with nutrient salts. Moreover, the N.E. monsoon winds probably have the effect of carrying the plankton from the open ocean towards the African coast, and by far the richest phytoplankton of the whole area was found at Station 101 (Gilson, 1937, pp. 52 and 54).

In the north-eastern area of the Arabian Sea hydrographic conditions are different. Here, at any rate during the period of our observations, there is considerable stability in the upper part of the water column, which would hinder the supply of nutrient salts from the rich stores of the water below by mixing. Nutrient salts may be brought to the surface layer by eddy transfer, a mechanism suggested by Seiwel (1935), by which exchange of nutrient salts may be brought about in very stable waters, and regeneration



of nutrient salts within the surface layer itself is not altogether improbable ; but in any case this area appears to be an unproductive one.

Another aspect of pH distribution related to the activity of the phytoplankton is that the maximum pH value of the surface waters does not as a rule occur at the very surface of the sea, but just below it. This feature was well-pronounced in the months of September–October at stations in the Gulf of Aden and in the north-eastern area of the Arabian Sea. Such an increase in photosynthetic activity below the surface has been attributed to the possibility that the light is too intense at the surface during these months (*cf.* Gilson, 1937, pp. 38, 39).

Finally, light has been thrown on the depth of the photosynthetic layer in the Gulf of Aden and in the north-eastern region of the Arabian Sea, especially during the months of September and October. Temperature and pH observations in these regions have shown the simultaneous development of maximum vertical pH and temperature gradients in the upper part of the water column at the same levels, a fact which has suggested that the depth of the photosynthetic layer was limited by the thermocline at the time of observation. The correspondence between the depths at which distinct pH and temperature vertical gradients occurred was less perfect during the other months. It is therefore concluded that the depth of the layer of phytoplanktonic activity in the regions under consideration is limited in the summer by the thermocline. A similar conclusion was arrived at by Seiwel (1935) with regard to the depth of this layer in the tropical North Atlantic from a study of the vertical distribution of phosphate and oxygen in the upper part of the water column. In view of this result it is suggested that during the winter months, owing to the absence of distinct thermal gradients in the upper part of the water column, the depth of the layer of phytoplanktonic activity in the north-eastern regions of the Arabian Sea is limited by light.

#### THE GEOCHEMICAL EFFECT OF THE ANTARCTIC BOTTOM CURRENT.

In the Arabian Sea, especially in its north-eastern basin, the pH values of the deep water in the vicinity of the bottom were found to be relatively high. It has been suggested that these high values are due to the geochemical effect of the Antarctic bottom current on the floor of the ocean. It is generally admitted that, on account of its origin, the Antarctic bottom current possesses a high content of carbon dioxide. By its solvent action under great pressures on the carbonate constituents of the ocean floor the water acquires a higher pH and the carbonate-content of the sediments decreases.

The character of the sediments, obtained by the present Expedition from Stations 166 and 167, which indicates a poor content of carbonate, strengthens this view. A process of re-solution of calcareous sediments from the floor of the Arabian Sea is therefore presumably taking place at its greatest depths. Similar views on the relation between the poor carbonate content of the sediments and the Antarctic bottom current have been put forward by Wattenberg (1933) and Wüst (1934).

#### SUMMARY.

1. The pH observations made on the waters of all oceans and seas until 1934 are reviewed.
2. The details of a colorimetric method used by the John Murray Expedition for the

determination of the values of pH on board H.E.M.S. "Mabahiss" during her cruises in 1933-1934 are given and discussed.

3. The observations so obtained at 82 stations distributed over the area of the north-western Indian Ocean and its adjoining gulfs are reduced into such forms which make them comparable with other recent and old pH data given in the literature.

4. The vertical distribution of pH along thirteen sections and its horizontal distribution at thirteen levels in the area investigated are graphically illustrated and described.

5. Short-period variations of pH in certain regions of the area investigated are described and their bearing on the representativeness of our observations is discussed.

6. The distribution of pH is discussed and several conclusions regarding the origin, character and movement of water masses in the north-western Indian Ocean and its adjoining gulfs, the activity of the phytoplankton in the upper part of the water column and certain geochemical processes in the deeper water are deduced therefrom.

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## APPENDIX

## A NOTE ON THE DETERMINATION OF HYDROGEN SULPHIDE IN SEA-WATER WITHDRAWN FROM CERTAIN SAMPLES OF MUD COLLECTED FROM THE NORTH-WESTERN INDIAN OCEAN.

## INTRODUCTION.

The discovery by the John Murray Expedition of an area in the Arabian Sea in which there was a complete absence of life has been of wide interest. Throughout this area the bottom consisted of a soft green mud, that in the neighbourhood of Ras el Hadd smelt strongly of hydrogen sulphide. Mud samples obtained from the lagoons of Addu, Fadiffolu and Horsburgh Maldivé atolls were also found to be impregnated with this gas in varying degrees. A slight trace of it was detected in a bottom deposit of green mud obtained at Station 189 off the Arabian coast in the Gulf of Aden. On this discovery I was called on to determine the hydrogen sulphide content of the water occluded in these mud samples.

## METHOD.

In view of the fact that no special chemical equipment was brought on board the "Mabahiss" to meet such an unexpected analysis, a method which is simple, rapid and convenient for use on board ship was employed. The analysis figures obtained by this method and recorded in this note do not claim any absolute significance. Defects which will be indicated in the course of this note, both in the technique employed in withdrawing the water from the mud and in the accuracy of the analytical method itself, make such an absolute significance remote. Nevertheless, the determinations were carried out with the purpose in view of exploratory quantitative study and of possible comparison with existing data from other dead regions.

With the exception of one sample, all the water samples were withdrawn from the mud by aspiration—a procedure which results in loss of gas and reduces therefore the  $\text{H}_2\text{S}$  content of the water aspirated off. This result is illustrated by the difference in the figures of analysis of three samples of water withdrawn from the same sample of mud (sample from Station 77) which are given in Table I.

TABLE I.

Water sample.	$\text{H}_2\text{S}$ mg./l.
(a) . . . . .	29.39
(b) . . . . .	23.77
(c) . . . . .	19.55

Sample (a) was obtained by simple filtration; samples (b) and (c) were aspirated off. Unfortunately this procedure of aspirating off the water from the mud had to be adopted because simple filtration was found to be extremely slow and gave water only in small quantities—insufficient for analytical purposes.

The method used for the determination of hydrogen sulphide consisted in adding a known excess of a standardized N/100 iodine solution in potassium iodide to a known volume of the water sample (100 c.c.) and titrating the iodine which was not reduced by hydrogen sulphide with sodium thiosulphate. The latter was standardized against iodate. Although the method, as already mentioned, is rapid and convenient for use on board ship, yet, as applied in sea-water analysis, it calls for analytical refinement, since its accuracy is limited by the interference of other reducing constituents of sea-water. Blank analysis carried out on  $\text{H}_2\text{S}$ -free water obtained from similar depths in the neighbouring regions suggests itself as a line of analytical refinement.

## RESULTS OF ANALYSIS.

In Table II are given the analysis figures of the  $\text{H}_2\text{S}$  content of the water aspirated off from the mud samples which are denoted by station numbers to be found in the List of Stations (Sewell, 1935), where data regarding position, date, etc. are given.

TABLE II.

Station.	Locality.	Sounding m.	Nature of bottom.	$\text{H}_2\text{S}$ mg./litre.
77	Gulf of Oman, off Ras el Hadd	421	gn. m.	29.39*
137	Addu Atoll anchorage	46	w. m.	4.90
142A	Fadiffolu Atoll, E. side	31	br. and w. m.	3.92
142B	Fadiffolu Atoll, W. side	37	cm. m.	2.26
160	Horsburgh Atoll, N. side	37	„	7.73
189	Gulf of Aden, off the Arabian coast	91	gn. s. m.	0.25

\* Water sample obtained by simple filtration.

It is seen from these analysis figures that the highest  $\text{H}_2\text{S}$  content was found at Station 77 off Ras el Hadd where there seemed to be a complete absence of life, and this azoic condition must be related in some way or another to the presence of hydrogen sulphide in the mud. The lowest  $\text{H}_2\text{S}$  content was found in the Gulf of Aden, but in the lagoons of Addu, Fadiffolu and Horsburgh Atolls its content varies from 2.26 to 7.73 mg./litre. The absence of coral growth from the lagoons of Horsburgh Atoll and the scarcity of the bottom fauna in that of Addu Atoll were reported by Stanley Gardiner (1903), and it is sound enough to conclude with Sewell (1936) that the presence of this gas in the lagoons “may well prove to be distinctly adverse to the coral growth or to the existence of other forms of animal life”.

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